RESEARCH ARTICLE

Recalibration of limits to growth

An update of the World3 model

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Abstract

After 50 years, there is still an ongoing debate about the Limits to Growth (LtG) study. This paper recalibrates the 2005 World3-03 model. The input parameters are changed to better match empirical data on world development. An iterative method is used to compute and optimize different parameter sets. This improved parameter set results in a World3 simulation that shows the same overshoot and collapse mode in the coming decade as the original business as usual scenario of the LtG standard run. The main effect of the recalibration update is to raise the peaks of most variables and move them a few years into the future. The parameters with the largest relative changes are those related to industrial capital lifetime, pollution transmission delay, and urban-industrial land development time.

KEYWORDS
crisis, industrial ecology, Limits to Growth, overshoot and collapse, system dynamics, World3

1 | INTRODUCTION

The Limits to Growth (LtG) is the name of a study conducted in the late 1960s for the Club of Rome. A group of researchers at the Massachusetts Institute of Technology developed a computer model that simulated some of the world's most important material variables, such as population, food production, resource use, and environmental impact. A total of 12 scenarios were presented in 1972 in the first book of the same name (Meadows et al., 1972). The scenarios cover the period from 1900 to 2100. The authors emphasize that the scenarios are not predictions. Rather, they are intended to illustrate the complex interrelationships within a dynamic system based on exponential growth.

The first and probably best known scenario is called the "standard run" or "business as usual" (BAU), which shows an exponential growth dynamic of the system and leads to the overshoot and collapse mode triggered by the depletion of non-renewable resources. The other scenarios describe changes in the parameterization of the model and assumptions about technological and societal developments. In the scenario called business as usual 2 (BAU2), twice as many initial non-renewable resources (NRI) were assumed and recycling technologies were implemented. These changes result in a different trajectory for each variable, but do not change the overshoot and collapse mode. The collapse in this case is caused by excessive pollution (Meadows et al., 1972). The scenario *comprehensive technology* (CT) assumes a very broad application of technological solutions. Thus, the pollution rate is greatly reduced, crop yields on agricultural land are greatly increased, and resource efficiency is set above all historical values (Herrington, 2021). The basic dynamics in this scenario are different from those mentioned above. The industrial variables as well as the food production still show exponential growth, but the population growth slows down and reaches a plateau from the middle of the analyzed time period. In this scenario, the collapse is postponed to the end of the time period under consideration, but there are some steep downward slopes at the end

(Meadows et al., 1972). The stabilized world (SW) scenario models a future state in which world population, industrial production, and resource consumption reach a steady state, resulting in a sustainable balance between human society and the environment. It is the only scenario in which the model variables are not in an overshoot and collapse mode (Meadows et al., 2005).

1.1 | The World3 model

The model used in LtG is called *World3* and is implemented in a system dynamics framework. System dynamics is a methodology for understanding complex systems and their behavior over time (Forrester, 1971). The full technical description of the World3 model was published in 1974 in the book *The Dynamics of Growth in a Finite World* by Meadows et al. (1974). There have been other major updates to the LtG. The most important was described in the book *Limits to Growth the 30-Years Update* (Meadows et al., 2005). In this update, a new adaptive technology sector was added to the model, now called World3-03, as well as two newly introduced world variables: ecological footprint (EF) and human welfare index (HWI). The standard run scenario in this book is called *business as usual 1* (BAU), the scenario with the assumption of more abundant resources is labeled BAU2.

The World3 model consists of the following five interrelated sectors:

- Population
- Capital
- Agriculture
- Non-renewable resources
- Pollution

There are two main positive feedback loops responsible for the exponential growth dynamics of the model. A larger population leads to a higher birth rate with a 15–30 year delay, and a higher investment rate leads to more industrial capital, which in turn allows for higher investment. But there are also limiting elements in other sectors. An example is the maximum arable land available for food production, or the assumption about the non-renewable resources needed for both food and industrial production (Meadows et al., 1974).

1.2 | Reviews and critics

Since the publication of LtG, countless reviews, critiques, and statements have been written on the subject. Some of these are briefly presented here. A more comprehensive overview of the LtG debate can be found in Jackson and Webster (2016). The authors summarize the debate since the 1970s and relate the topic to modern concepts such as the *Planetary Boundaries* of Rockström et al. (2009).

Turner (2008) found that 30 years of historical data best fit the standard run scenario of the original World3 model. An update of this study in 2012 concluded that even after 40 years of empirical data, the standard run is still the best fitting scenario. The authors also analyzed the causes of the collapse seen in the model's results and related them to the peak oil debate (Turner, 2012).

The latest data comparison by Herrington (2021) was made with the 2005 version of the World3 model, including the newly introduced variables *HWI* and *ecological footprint*. The author found that, in contrast to previous comparisons, the closest matching scenarios were BAU2 and CT. These divergent results may also be due to slightly different comparison parameters and the use of the 1972 version of World3 by Turner (2008) and the updated 2005 version of the model by Herrington (2021).

LtG was also subject to much criticism, for example, by Rubin and Lomborg (2003). A good overview is given in the book *Limits to Growth* revisited by Bardi (2011). The author describes that early criticisms of LtG often referred to overly pessimistic assumptions about, for example, available agricultural land or mineral resources. Over time, this has been disproved by real-world developments or extraction technology that is still lacking behind what the critics expected at that time. The methodology of system dynamics was also criticized for its ability to do "measurements without data" (Nordhaus, 1973). Major criticism also stems from neo-liberal economists (Jacques et al., 2008). They claim that the authors of LtG underestimated human ingenuity and the ability to develop technologies, that would solve any impending crisis or scarcity. The effects of a market-based society were also not taken into account enough, that is, the incentive to find alternatives, triggered by scarcity and thus increasing prices of resources (Norgard et al., 2010).

Many of these critics focus on one single scenario and interpret it as an exact prediction of the future. The authors of LtG have always emphasized that their scenarios are not exact predictions. Above all, the main goal of LtG is to show the behavior of a complex dynamic system and describe possible developments on the basis of different scenarios. One of the core statements of LtG is also the plurality of limits and that the overshoot and collapse dynamics remained, even with different boundary conditions, political interventions and assumptions (Herrington, 2021).

1.3 | Motivation

As described in the review section, the debate around the actuality of the LtG is still ongoing. The authors' warnings in 1972 about reaching various of Earth's system boundaries were largely ignored. Fifty years later, some vulnerable limits described by the framework of planetary boundaries have already been crossed (Persson et al., 2022).

Previous data comparisons of model data with the measurable variables of the Earth still showed a high degree of similarity. For this paper, the existing approach of only comparing the data should be extended. Since the model was calibrated with the limited capabilities in terms of computing power and data processing in 1972, it seems interesting to what extent a recalibration of the model is possible and what are the effects of such a recalibration. The data situation has improved enormously since then and furthermore the model can be run multiple times using the algorithm developed here, to heuristically approach an optimal parameter configuration. Another point is that the peak of the original BAU scenario should fall approximately in the present time. Therefore, a parameter update could also provide relevant information on what the model indicates about the general dynamics of global material and socio-economic developments in the future, such as the approximate timing of the onset and main cause of a collapse.

This leads to the following question for this paper: Which parameters need to be adjusted to make the World3-03 model more consistent with today's empirical data, and what would the resulting scenario look like?

For this purpose, the methodology is presented in Section 2. This includes the Python implementation of the World3 model and the update of it. Furthermore, the presentation of the data basis and finally the heuristics according to which the model parameters were recalibrated. Section 3 presents the results. Some of the changed parameters are discussed and a new scenario is shown. Furthermore, the robustness of the results and a sensitivity analysis are discussed. Finally, the results are discussed in Section 4.

2 | METHODS

Today, extensive online data sources and powerful computers allow for more accurate and faster modeling and data comparison than was possible in 1972. This paper takes advantage of this by using a Python implementation of Vanwynsberghe (2021) as a base model and updating it to the latest version of World3. The model data (MD) is then compared to the empirical data (ED) using a statistical measure to determine the difference. To minimize the divergence, selected parameters are varied and the results are iteratively improved.

2.1 | PyWorld3 update

The PyWorld3 model is a Python implementation of the World3 model (Vanwynsberghe, 2021). It is based on the technical description (Meadows et al., 1974). Thus PyWorld3 reflects the World3 version from the first book in the *Limits to Growth* series. In order to obtain actual results, PyWorld3 is updated to the version used in the book "*Limits to Growth: The 30-Year Update*" (Meadows et al., 2005). This book includes a CD with the updated version of World3, written in the programming language STELLA. This version is used to update PyWorld3 to the 2005 edition "PyWorld3-03." The code of the developed PyWorld3-03 is published and can be found in GitHub (https://github.com/TimSchell98/PyWorld3-03). The basic functionality of PyWorld3 is still available, since nothing fundamental has been changed. Only the variables and the equations connecting the variables have been updated to the World3-03 version of 2005.

2.2 | Empirical data

For comparison and recalibration, it is essential to have appropriate and accurate empirical data (ED). Therefore, a comparison variable for each sector, such as CO_2 concentration for pollution, and the associated data must be selected. The scope of the ED of this study is comparable to that of Herrington (2021). Most of its procedures fit the inputs required here. Several data sets have been adopted and updated. This selection is explained below for each of the sectors.

Population data is available at The World Bank (2023b). Since the model uses the number of people to represent the population, no conversion is required.

Industrial output (IO) data measured in dollar equivalent per person per year in LtG (Meadows et al., 1972) is not an existing empirical data set. Therefore the Index of Industrial Production (IIP) is used as proxy. It details the growth of the capacity of industrial production, excluding price fluctuations (United Nations Industrial Development Organization, 2023b). The data is only available for each country, but not globally at United Nations Industrial Development Organization (2023a). It is based on the year 2015 (United Nations Industrial Development Organization,

2023b), which means that the value for each country in the year 2015 is 100. Therefore, the national manufacturing value added is used as the weight, also accessed from United Nations Industrial Development Organization (2023c). To compare the IO of LtG with the weighted index using a statistical measure, a conversation is required. Due to two different units, the relative change for each year, here called the change rate (CR), is calculated. Equation (1) shows the calculation of the change rate for the year t.

$$CR_t = \frac{ED_t - ED_{t-1}}{ED_{t-1}} \tag{1}$$

Food per capita is originally expressed in vegetable equivalents (Meadows et al., 1972). The empirical data use kilocalories per person per day (FAO, 2023). The conversion factor of 3500 kilocalories per kilogram of vegetable food is applied, as in the description of LtG (Meadows et al., 1974). However, since the two graphs are still shifted on the *y*-axis, the change rate method is also used to compare the modeled data with the empirical data.

Pollution, expressed in pollution units (Meadows et al., 1972), includes all substances emitted into the environment. To approximate the data set, the CO_2 concentration is used as a proxy. CO_2 is usually emitted when other pollutants occur. It is also the most commonly used measure when talking about pollution. The data for the global CO_2 concentration in ppm is available from Lan et al. (2023). The change rate method is used because the units of the two data sets are different.

Non-renewable resources, measured in resource units Meadows et al. (1972), include all non-renewable resources on Earth. The exact amount is not known and probably never will be. Since this implies the use of the change rate method for this sector, a derivation of the variable can be used instead of absolute values. In order to provide suitable and accurate data, fossil fuel consumption is chosen. Although this proxy does not include metal resources, it is the most appropriate and available data. The data set is derived from Our World in Data (2022) with reference to Vaclav Smil (2016) and bp (2022).

Service per capita, used in LtG (Meadows et al., 1972) is measured in dollars and combines all expenditures in the service sector, such as medical care and education. The education index is used to emulate this sector. Although it captures only part of the sector, it is the best available proxy. Education is one of the main components of the service sector and is correlated with the rest of the sector. The data is taken from Human Development Reports (2022a) and the change rate method is used.

Human welfare is detailed by the Human Development Index (HDI). Since World3-03 it is part of the model, so it is also calculated in this updated version of PyWorld3-03 and can be compared directly. The United Nations Development Program calculates and publishes the data (Human Development Reports, 2022b).

Ecological footprint (EF) is also part of the model. The empirical data is taken from York University Ecological Footprint Initiative & Global Footprint Network (2022) and can be directly compared with the modeled data.

The industrial output, food, pollution, resource, and service data are smoothed. To reduce unwanted high frequency fluctuations in the data sets and to avoid any phase shift into the future, the sectors are averaged using a filter applied in both time directions.

2.3 | Recalibration process

To determine the accuracy between the model data (MD) and the empirical data (ED), the normalized root mean square deviation (NRMSD) is used (Turner, 2012). This statistical measure of difference normalizes the root mean square to the ED, which allows different sectors to be compared. The calculations are performed at a 1-year interval, which is the step size t of the model and the empirical data. The deviation is calculated for N times, depending on the number of data steps available. Equation (2) shows an example of a calculation starting in 1970 (Herrington, 2021).

$$NRMSD = \frac{\sqrt{\frac{\sum_{t=0}^{N}(MD_{1970+t} - ED_{1970+t})^2}{N}}}{\frac{\sum_{t=0}^{N}(ED_{1970+t})}{N}} \tag{2}$$

NRMSD is calculated for each sector of the model using the most recent data for the last 50 years. For the services sector, only 30 years of data are available and therefore calculated. To provide a single measure of quality for a given set of parameters, the NRMSD total is implemented. It is calculated by weighting the NRMSD of each variable by a selected factor and then taking the mean. The weighting is based on the accuracy of the data. Therefore, the variables are weighted as follows:

- Population = 1
- Industrial output = 0.5
- Food per capita = 0.7
- Pollution = 0.5

- Non-renewable resources = 0.5
- Service per capita = 0.5
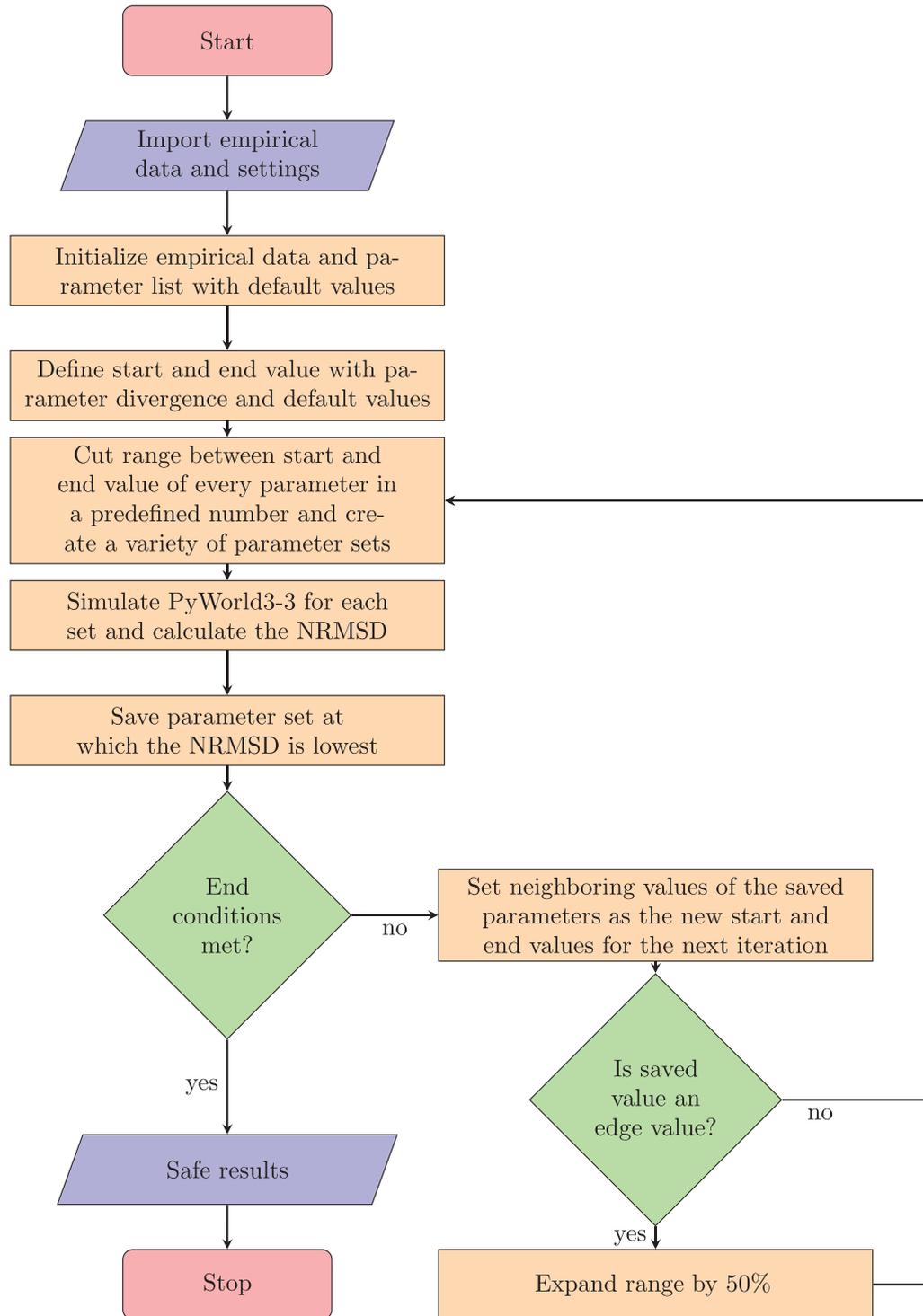- Human welfare = 0.7
- Ecological footprint = 0.7

FIGURE 1   Flow chart of the used algorithm to find an optimal parameter set.

The model best represents the empirical data when the NRMSD is minimal. To find an optimal parameter set, a Python script was created to run multiple simulations in PyWorld3-03. For the script, 35 of the model parameters are selected for possible recalibration. Some parameters, such as the initial population in 1900, are not considered because they are already observed values and should not be changed.

The main results of this paper will be referred to as "Recalibration23." Figure 1 shows the flow chart to determine the desired recalibration of the parameter sets. The first iteration starts with the default values from BAU2. The range in which each parameter can be varied in the course of one iteration is set to a predefined value of 50% and 150%. Another predefined setting called "grid resolution" divides the range between the start
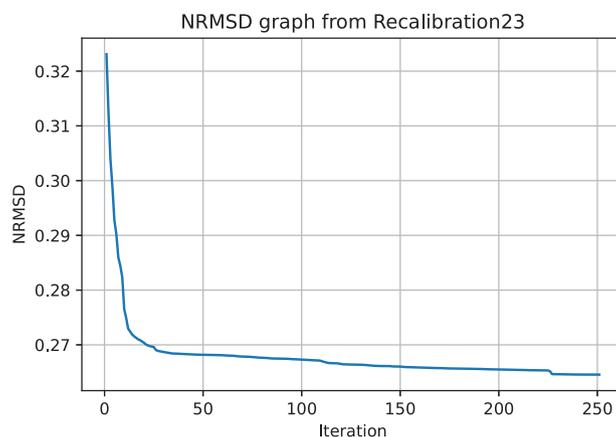
FIGURE 2 Normalized root mean square deviation course from Recalibration23 over the iterations. The underlying data for this figure are available in Table S2 of Supporting Information S1.

TABLE 1 Normalized root mean square deviation comparison: Recalibration23, business as usual (BAU), and business as usual 2 (BAU2).

Sector	Recalibration23	BAU	BAU2
Total	0.2719	0.3318	0.3474
Population	0.0183	0.0213	0.0237
Industrial output	0.4740	0.8062	1.5463
Food per capita	1.1079	1.0589	0.9911
Pollution	0.3371	0.6753	0.3873
Non-renewable resources	0.7571	0.7027	0.8729
Service per capita	0.6188	0.9289	1.0103
Human welfare	0.1783	0.089	0.1121
Ecological footprint	0.3425	0.4622	0.3337

and end values. In Recalibration23 this setting is set to 60. With these and the default values of the other parameters, the PyWorld3-03 simulation is run.

The NRMSD is calculated for each simulation. After each parameter is changed, the parameter set with the lowest NRMSD is saved and used for the next iteration. After the first iteration, the values before and after the optimal parameter value from the last iteration are used as the start and end values. If the optimal parameter value is either below the start value or above the end value, the range is expanded. When a certain end condition is reached, the analysis stops. The end condition can be either the number of iterations or the difference between the NRMSD of the current iteration and the last iteration.

The course of the minimal NRMSD of Recalibration23 over the iterations is shown in Figure 2. The NRMSD decreases sharply in the first 20 iterations. After that, the graph converges to the lowest possible NRMSD for the chosen settings. In this case, the minimal NRMSD is about 0.28.

3 | RESULTS

Using this approach, a set of parameters is calculated, which are shown and explained in this section. Sensitivity analyses were also performed by changing the initial parameters and the weighting.
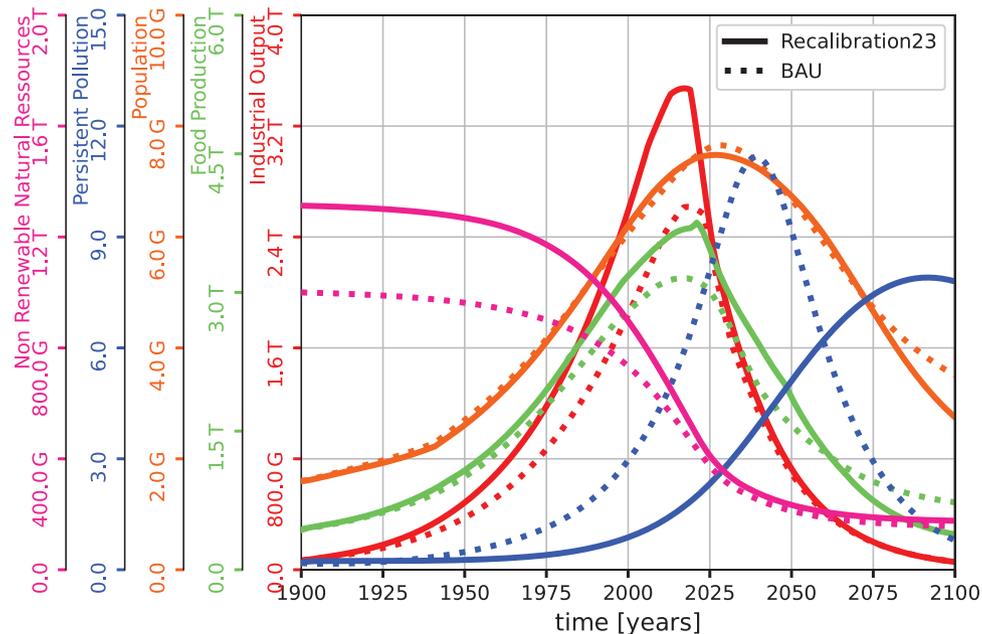
3.1 | Recalibration23

The recalibrated parameter set improves the NRMSD by 18.05%, from 0.3318 in the BAU scenario to 0.2719 in the Recalibration23 scenario. All NRMSD values are shown in Table 1. The modified parameters with their full names, default values, improved values, and relative change are shown in Table 2. In addition, a graph of key variables from the Recalibration23 scenario is shown in Figure 3. Graphs comparing the variables population

TABLE 2 Parameters with improved and default values and relative change of Recalibration23.

Parameter	Full name	Default value	Improved value	Relative change [%]
alic1	Average lifetime of industrial capital 1	2.00	15.24	662.15
pptd	Persistent pollution transmission delay	20.00	116.38	481.92
hsid	Health services impact delay	20.00	38.24	91.18
lpd	ILifetime perception delay	20.00	33.84	69.20
ppgf1	Persistent pollution Gen Fact 1	1.00	1.53	53.44
lfpf	Labor force participation fraction	0.75	1.02	36.21
alln	Average life of land normal	1000.00	1351.20	35.12
palt	Potentially arable land total	3.20E+09	4.22E+09	31.77
nri	Non-renewable resources initial	1.00E+12	1.30E+12	30.23
imti	Industrial material toxic index	10.00	11.06	10.64
imef	Industrial material emission factor	0.10	0.11	10.17
pl	Processing loss	0.10	0.10	4.05
frpm	Effective fraction of resource utilization on pollution generation	0.02	0.02	3.34
sfpc	Subsistence food per capita	230.00	233.69	1.61
faipm	Effective fraction of agricultural pollution input	0.001	0.001	−5.60
sd	Social discount	0.07	0.06	−13.64
mtfn	Maximum total fertility normal	12.00	9.45	−21.22
amti	Agricultural material toxicity index	1.00	0.77	−23.13
sad	Social adjustment delay	20.00	13.38	−33.08
fspd	Food shortage perception delay	2.00	0.61	−69.42
uildt	Urban-industrial land development time	10.00	0.53	−94.67

FIGURE 3 Recalibration23, improved run compared to BAU. The underlying data for this figure are available in Table S3 of Supporting Information S1.
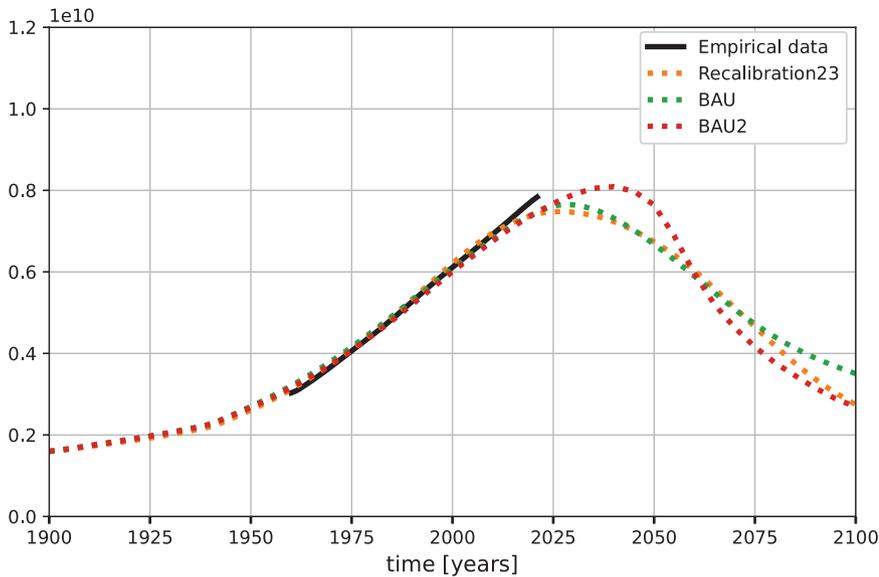
Scenario Comparison Population

FIGURE 4 Empirical data, original business as usual and business as usual 2 scenario, and the new Recalibration23 scenario are plotted for the variable population. The underlying data for this figure are available in Table S4 of Supporting Information S1.
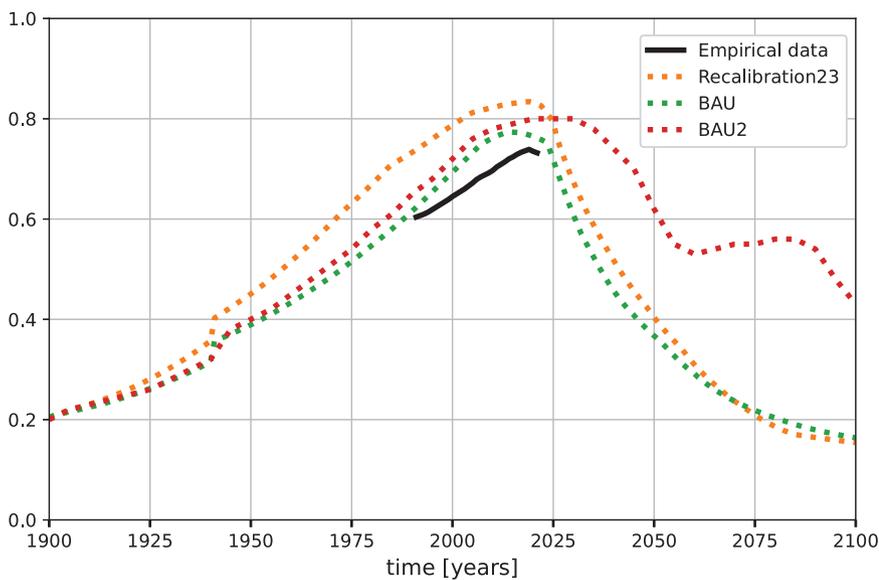
Scenario Comparison HWI

FIGURE 5 Empirical data, original business as usual and business as usual 2 scenario, and the new Recalibration23 scenario are plotted for the variable Human Welfare Index. The underlying data for this figure are available in Table S5 of Supporting Information S1.

(Figure 4) and HWI (Figure 5) of the scenarios Recalibration23, BAU, and BAU2 are discussed.

Figure 3 shows not only the results of specific Recalibration23 variables, but also the values of the same variables from the 2005 reference run (BAU). The rough trajectories of non-renewable resources, industrial output, and food do not differ much from BAU. Only the timing and height of the peaks are different. The food peak is higher and shifts a few years into the future. A similar behavior can be seen in the industrial curve, the peak rises, but moves into the past. The initial resource value is higher than in BAU, but the curve of the graph still follows the same course and the approximate value of this variable for today is almost the same. The population curve is almost identical to BAU. The biggest difference is in the trajectory of the pollution. The peak of the curve declines and shifts about 50 years into the future. A further explanation of the variables that contribute to this changed trajectory is given in Section 4.

In addition to this "standard graph," which can be found in every LtG publication, specific graphs are created showing the population (see Figure 4) and the HWI (see Figure 5) of the newly created parameter set, BAU, BAU2, and empirical data. Figure 4 shows that each scenario is very similar to the empirical data of the human population. This is also visible in Table 1. The NRMSD of the population sector is the smallest in every scenario. The Recalibration23 scenario has the lowest NRMSD, followed by the BAU scenario.

Figure 5 shows a seemingly contradictory graph. The basic course of the HWI is very similar in all scenarios, except for the rebound peak in the BAU2 scenario. However, the BAU scenario shows the smallest deviation from the empirical data. The Recalibrated23 parameter set results in a

relatively large difference. This deviation can be seen in Table 1. The total NRMSD of the main results is still the smallest of the three scenarios, because the NRMSD of the other sectors is similar or smaller compared to both BAU scenarios.

In the recalibration algorithm, most parameters are improved only once or twice, while a few are improved dozens of times. The parameter "average lifetime of industrial capital 1" (alic1) has the highest relative change. The improved value is more than six times the default value. The value changes from 2 to 15.24 years. The second highest relative change has the persistent pollution transmission delay (pptd). This parameter increases from 20 to 111.8 years.

3.2 | Comparison with BAU and BAU2

Previous research by Turner (2012) and Herrington (2021) compared model results with empirical data. This paper focuses primarily on a recalibration of the model, but comparisons of empirical data with the BAU and BAU2 scenarios are also carried out. Table 1 shows these results for the individual sectors. Overall NRMSD results differ by only 0.0156 between BAU and BAU2, but according to our method used and our calculation BAU is more consistent with the empirical data.

A closer look at the individual sectors reveals greater differences. In the variables population and food per capita, the two scenarios are very close to each other. Industrial output and pollution differ significantly more, with the former matching closer to BAU and the latter to BAU2. For non-renewable resources, the difference in NRMSD is about 0.17. BAU is closer to the empirical data here. BAU2 assumes twice as many resources as well as existing recycling technology and does not end in collapse due to a lack of resources. Special attention can be paid to this. However, both the differences in the opposite direction and the weighting mentioned above lead to the fact that the two scenarios differ only slightly in the overall result.

3.3 | Sensitivity analysis

In addition to Recalibration23, several other optimizations are performed. First, a sensitivity to different weightings in the NRMSD calculation and second, a variation of the start values.

To measure how robust the analysis is to changes in the weighting system, two alternative weightings are analyzed. The first is an inverse weighting in which the population, HWI, and EF are weighted lower. The second alternative weighting increases the values of the variables compared with the change rate method. The change rate method uses Equation (1) to compare two data sets of ED and MD when they have different units. As expected, the changes in weighting have an impact on the optimization of each sector; the higher a sector is weighted, the greater its impact on minimizing the total NRMSD. However, the two weighting variations tested resulted in a higher overall NRMSD, even though individual sectors had lower NRMSDs in some cases. The weighting chosen in Recalibration23 can therefore be considered reasonable.

To investigate the influence of the initial NRI value on the results, the recalibration is performed with doubled, halved, and the same initial NRI values as in the BAU scenario. This investigation shows that the initial values of each parameter have an influence on the recalibration result. With the BAU initial value, an optimized parameter set is calculated in which the final NRI is set even slightly lower than its starting point. The halved initial value had almost no effect on the result, as the NRI was set to a value almost identical to the original initial value. The double initial value, as in BAU2, provides a recalibration result with a value between the two scenarios for the NRI parameter. The total NRMSD is actually slightly lower than what can be achieved with the default NRI start value from BAU.

As a result of this sensitivity analysis, it is clear that both the initial values and the weightings have an impact on the results. Each new combination represents a new optimization problem for the heuristic, resulting in a different set of parameters. Depending on the initial variables and the weighting, the recalibration starts in a different direction, that is, with different parameters. It is possible to find a local minimum of the NRMSD that is not the global one. To be confident that the best possible set of parameters has been found, several recalibrations are performed with different settings. The comparisons show that the minima are within a small range. It is likely that there are other combinations than those considered here that could lead to an even lower NRMSD, and it is always possible to obtain only a local minimum of the NRMSD. However, a systematic search of the solution space is beyond the scope of this paper.

The sensitivity of the World3 model to a change in initial parameters has been a source of criticism since the beginning of the LtG study (Castro, 2012; de Jongh, 1978; Vermeulen & de Jongh, 1976). But as Turner (2013) and Herrington (2022) argue, it is the dynamics of the system that is most important, not the value of a particular parameter at a particular point in time. All of the sensitivity calculations mentioned here show a similar overshoot and collapse pattern for the key variables, that is, they are robust to the parameter variations done in this paper.

4 | DISCUSSION

The discussion is divided into three parts. The first part analyzes the results from 1900 to the present. The second part points out the limitations. Finally, the third part gives an outlook on future trends.

4.1 | World3 and empirical data

In response to the key question, a new set of recalibrated parameters is presented that models the empirical data more closely than the original 1972 model. Since the studies by Turner (2012) and Herrington (2021) differ slightly, an additional question is whether BAU or BAU2 is closer to today's data. For this purpose, the two scenarios are compared using NRMSD as a statistical measure. In Table 1, the results show that with the weighting chosen in this paper, BAU is slightly closer to the empirical data than BAU2. Only the pollution sector of BAU2 is significantly more accurate. On the other hand, the NRMSD of the resource sector of BAU is lower. In summary, the empirical data fit best somewhere between BAU and BAU2. With the new parameter set of Recalibration23, the overall NRMSD is greatly improved compared to the difference between BAU and BAU2.

The population collapse shown in Figure 3 occurs a few years later with a higher number of people. The most significant change is the shift of the pollution curve. It peaks about 50 years later and reaches a higher value. The reason for the collapse in the recalibrated model is still resource depletion as in BAU, not pollution overshoot as in BAU2. This corresponds to the work of Turner (2012).

The industrial sector in the recalibrated model remains close to BAU. According to the industrial output graph in Figure 3, the peak has been reached today. This is in line with the observed data, as the IIP also shows declining growth in recent years, although a turning point is not yet visible. Accordingly, the parameters of the capital sector do not change in a wide range. For example, "industrial capital-output ratio 1" and "income expectation averaging time" are not changed. In BAU and the new scenario, decreasing industrial output is associated with a food shortage. With less industrial output, "total agriculture investment" decreases, among other things (Meadows et al., 1972). As a consequence, the whole system collapses and the death rate rises. In contrast to BAU, in the recalibrated model food is available for a few more years, shifting the population graph evenly on the time axis.

This turnaround exposed by the data for the Industrial Production Index is also visible in the HWI and in the services sector, since both are related to the education index. For these sectors, the data show not only declining growth, but already an absolute decline. The HWI starts decreasing in the year 2019, see Figure 5 (Human Development Reports, 2022b) and the education index begins to fall in the year 2021 (Human Development Reports, 2022a). Furthermore the death rate increases in 2020 for the first time since 1964 (The World Bank, 2023a). In the World3 model the HWI is calculated as the average of three indices: "lei" (life expectancy index), "ei" (education index), and "gdpi" (gross domestic production index). The first index, "lei," is based on perceived life expectancy, while the other two indices, "ei" and "gdpi," are based on gross domestic production.

Although the model suggests and the data indicates LtG, the origin is ambiguous. The resource and pollution sectors, which could be the origin in regard to LtG, are the most inaccurate data sets. The recalibrated version of World3 delays the pollution problem. Given these limitations, it is not entirely clear whether the collapse is caused by climate change resulting from pollution or by resource depletion, as implied by the recalibration. The effect of the pollution on the climate and consequently industry is already measurable (IPCC, 2022). Another possibility is the resource scarcity as a reason for the visible decline of economic growth. A detailed analysis of this possibility can be found in Turner (2012). Here, the development of the energy return on energy investment of oil is considered. Its steady decline indicates a gradual depletion of fossil energy resources.

4.2 | Limitations

The biggest limitation is the availability of empirical data. Of course, it is much easier to collect data now than it was in 1972. Still, it is very difficult to find data that represent a complete sector of the world. For population, food, the ecological footprint, and the HWI, this is straightforward, as explained in Section 2.2. Other sectors such as pollution and services cannot be quantified with a single set of empirical data. Therefore, a proxy such as CO_2 concentration or the education index is used. This is an approximation because the proxy only covers part of the sector. Industrial production, like others, is included by converting industrial output to dollars and comparing it to the IIP via their change rates. The same applies to the resources sector. In addition to the limitations of using the rate of change for comparison, the pollution sector is extremely complex to characterize. Many factors such as air pollution, toxics, plastics, and many others affect this sector. The proxy CO_2 is chosen because global data are available for a long period of time. This simplification may be the reason for the shifted pollution curve, because the emission of CO_2 does not cover the wide range of pollutants and is not fully represented in the measured atmospheric concentration due to absorption mechanisms. In addition, its impact on climate change is delayed and extends far into the future. Analyzing the impact of pollution on the other sectors and exploring a better representation in the empirical data could be part of further research in this area.

The recalibration of World3 adds an optimized set of parameters to the model. As a result, the simulation approximates the most recent empirical data. Considering the new recalibrated model, the existing limitations are still in force. As mentioned in Section 1.2, the model does not provide an exact prediction, but reflects the behavior and trends of a complex dynamic system. The collapse of the system is due to resource depletion in BAU or pollution in BAU2. But these two sectors are the most difficult to compare with empirical data. Therefore, especially the accuracy of the timing of the peak cannot be relied upon.

Another uncertainty is the impact of crises, such as the 2008 financial crisis or the Covid-19 pandemic. These are reflected in the empirical data, for example, the increase in mortality in 2020 or the decrease in IPP in 2008 and 2020. However, LtG as a model is not able to reproduce these short-term events. Rather, it serves to reveal broad trends and dynamics (Meadows et al., 1972).

4.3 | Future trends

So far, the results have mainly been considered in comparison with the empirical data for the recalibration. However, the course of the variables is also interesting in terms of future trends. Here, the model results clearly indicate the imminent end of the exponential growth curve. The excessive consumption of resources by industry and industrial agriculture to feed a growing world population is depleting reserves to the point where the system is no longer sustainable. Pollution lags behind industrial growth and does not peak until the end of the century. Peaks are followed by sharp declines in several characteristics.

This interconnected collapse, or, as it has been called by Heinberg and Miller (2023), polycrisis, occurring between 2024 and 2030 is caused by resource depletion, not pollution. The increase in environmental pollution occurs later and with a lower peak (Figure 3).

However, it is important to note that the connections in the model and the recalibration are only valid for the rising edge, as many of the variables and equations represented in the model are not physical but socio-economic. It is to be expected that the complex socio-economic relationships will be rearranged and reconnected in the event of a collapse. World3 holds the relationships between variables constant. Therefore it is not useful to draw further conclusions from the trajectory after the tipping points. Rather, it is important to recognize that there are large uncertainties about the trajectory from then on, building models for this could be a whole new field of research.

The fact is that the recalibrated model again shows the possibility of a collapse of our current system. At the same time, the BAU scenario of the 1972 model is shown to be alarmingly consistent with the most recently collected empirical data.

Herrington (2021) also concluded in her data comparison that the world is far from a stabilized world scenario where the overshoot and collapse mode is brought to a halt. As a society, we have to admit that despite 50 years of knowledge about the dynamics of the collapse of our life support systems, we have failed to initiate a systematic change to prevent this collapse. It is becoming increasingly clear that, despite technological advances, the change needed to put us on a different trajectory will also require a change in belief systems, mindsets, and the way we organize our society (Irwin, 2015; Wamsler & Brink, 2018).

At the point of collapse, the resolution of the model also reaches the limit of further plausible statements. The regional differences in demographic and economic terms are too great to be reduced to simple, highly aggregated variables. To address this problem, a new system dynamics model has been developed on the occasion of LtG's 50th anniversary which is called Earth for all (Sandrine Dixson-Decleve et al., 2022). It introduces a regional resolution and a measure of social inequality and tension. There is also a greater focus on the causes and effects of the climate crisis. In Earth4all, the authors no longer focus on scenarios with sharp declines in the main variables. Instead, the scenario *Too little too late* describes that the effects of the climate crisis will continue to increase and social tensions will rise, causing the well-being index to decline over time. In another scenario, *Giant leap*, it is shown that these negative developments could also be stopped. The authors then propose various policy changes to achieve this (Sandrine Dixson-Decleve et al., 2022).

5 | CONCLUSION

In this paper, the World3 model of the LtG study has been recalibrated to reflect the behavior of empirical data over the last 50 years. For this purpose, 35 parameters of the model were selected and optimized for a selected set of eight different empirical data sets that most closely reflect historical developments. An algorithm was developed to minimize the aggregated NRMSD between the model data and the empirical data using an iterative method. A new scenario with the improved parameter set was presented. Of the original 1972 LtG scenarios, the BAU scenario matches these parameters and the evolution of the variables most closely. Like the BAU scenario of the LtG publication, the new scenario *Recalibration23* reflects the overshoot and collapse mode due to resource scarcity. However, the peaks of certain variables are raised and partially shifted into the future.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.