Sensitivity of Population/Resource Dynamics to Pandemic-Scale Variation in Life Expectancy

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Abstract

How do pandemics affect population/resource dynamics, and conversely? Canonical compartmental epidemiological models such as SEIRD do not address nominally non-pandemic population/resource variables such as food production, industrial production, and pollution generation and thus cannot answer this question. Using the World3 population/resource dynamics simulator, I compute the sensitivity of approximately 200 population/resource variables to pandemic-scale variation in life expectancy. The results suggest that the population/resource-management policies and practices of World3's "Scenario 9" can strongly mitigate the fiscal and physical disruption of some pandemics.

Keywords: *population/resource dynamics, pandemic dynamics*

1.0 Introduction

Compartmental epidemiological models (Vynnycky and White 2010) such as SEIRD (whose compartments are Susceptible, Exposed, Infected, Recovered, and Deceased) represent population-disease dynamics without regard to how those dynamics interact with nominally non-pandemic global population/resource factors such as food production, industrial production, capital investment, pollution generation, and non-renewable resource consumption. In order to assess the interaction between pandemic-, and population/resource-, dynamics, we need a model that integrates these regimes.

There is at least one clear connection between the dynamics of compartmental epidemiological models and population/resource dynamics. At the beginning of a global pandemic caused by a novel highly transmissible infectious agent, in the absence of effective control modalities (vaccination, masking, social distancing, etc.), the SEIRD Susceptible population *is* the world population.

The *World3* simulator (Meadows et al. 1974; Cellier 2008; Cellier 2019; Wolfram 2019) models, at a high level, the dynamical interaction of world population, pollution, agriculture, capital, non-renewable resources, and the effect of health services on life expectancy. Although *World3* does not explicitly model pandemic dynamics per se, it is possible to appropriate *World3*'s parametric modeling of the effect of health services on *World3*'s variable **Life Expectancy** as a proxy for those pandemic effects on life expectancy that can be approximated by varying a (parameter) multiplier of the non-pandemic life expectancy values. Details of this proxy are described in Section 2.0.

Pandemic regimes in which this kind of approximation is informative are those in which, given a specific infectious agent (e.g., a specific variant of a virus), and the time interval of interest, are such that:

a. At the beginning of the pandemic, the world population has no immunity to infection by the agent
b. There is no significant control of the spread of the disease, and
c. The fraction of the susceptible population that has been infected is small (nominally < 10%)

The beginning of the 1918 influenza pandemic satisfied (a) - (c) (Spreeuwenberg, Kroneman, and Paget 2018). The COVID-19 pandemic as of August 2022, because the dominant strain of the virus has been changing faster than fully effective control measures have been globally deployed, roughly approximates (a) – (c) (Johns Hopkins University 2022).

1.1 Brief history of *World3*

World3's behavior is reasonably well understood (Turner 2014; Herrington 2020). It evolved from the *Limits to Growth* project (Meadows et al. 1974), launched in the early 1970s. The objective of the *Limits to Growth* project was to determine whether systems analysis techniques developed by Jay Forrester and colleagues at MIT "could provide new perspectives on the interlocking complex of costs and benefits inherent in continued physical growth on a finite planet" (Meadows et al. 1974, vii).

In the first two decades of its existence, the *Limits to Growth* family of world dynamics simulators was extensively criticized (Simon and Kahn 1984; Simon 1996; Cole et al. 1973). More recent assessments (Turner 2008; Turner 2014; Randers 2012; Nørgård, Peet, and Ragnarsdóttir 2010; Herrington 2020), however, argue that *World3* (especially *World3*'s Benchmark Scenario 1; see Section 1.3 of this paper) has predicted the trajectory of the global population, and food production per capita, well. Table 1, for example, compares the population predictions of *World3*'s "Business as Usual" scenario (see Scenario 1, Section 1.3, below) with UN estimates (UN 2019) of the world population, 1970 to 2020.

Table 1. Comparison of some *World3*'s population predictions (from the "Business as Usual" Scenario; see Section 1.3 below) with the UN estimates (UN 2019). Population is rounded to two significant figures; percent difference is rounded to one significant figure.

Year	***World3* prediction of world population (billions, from BAU Scenario)**	**UN estimate of world population (billions)**	**Percent difference between World3 prediction, and UN estimate, relative to UN estimate**
1970	3.9	3.7	5
1980	4.6	4.5	2
1990	5.4	5.3	2
2000	6.2	6.1	2
2010	7.1	7.0	1
2020	7.9	7.8	1

Similarly, Table 2 compares *World3*'s BAU Scenario predictions of world food production per capita per year[1] with UN estimates of that quantity.

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[1] Meadows et al. 1974 estimate that 230 kilograms vegetable-equivalent production per capita per year is required for survival.

Table 2. Comparison of *World3*'s Benchmark Scenario 1 ("BAU") prediction of world food production with UN estimates (Roser and Ritchie 2022) of the same. Food production units are vegetable-equivalent kilocalories per person per year (see Meadows et al. 1974, p. 282 for a definition of this unit).

Year	***World3* prediction, Benchmark Scenario 1 ("BAU")**	**UN Estimate, normalized to *World3*'s 1970 prediction**	**Percent difference, relative to UN estimate**
1970	384	384	0
1980	407	400	2
1990	425	416	2
2000	430	432	0.5
2010	416	448	7
2020	390	464[2]	16

The *World3* BAU Scenario food production per capita per year magnitudes evidently agree well with UN estimates of the same, 1970-2000. The BAU predictions for food production are slightly more pessimistic than UN estimates for 2010 and 2020.

Herrington 2020 shows that current empirical data is broadly consistent with the 1972 *World3* projections, and that if major changes to the consumption of resources are not undertaken, economic growth will peak and then rapidly decline by around 2040.

World3 was originally written in DYNAMO (Pugh 1963) and was batch-oriented. By 2004, *World3* had been ported to the STELLA modeling language (Richmond 2013). Cellier 2008 is an object-oriented (Rumbaugh, Jacobson, and Booch 1999; Schlaer and Mellor 1992; Smith 1996) re-engineering of the 2004 (STELLA) version of *World3* to the Modelica (Open Modelica 2019; The Modelica Organization 2019) simulation language. Cellier 2019 is a re-engineering of Cellier 2008 to the *SystemModeler* (Wolfram 2019) simulation framework.

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[2] Predicted value. It does not take into account the effects of the COVID-19 pandemic or agricultural yield losses in sub-Saharan Africa. Collectively, these effects would likely reduce the UN estimate about 10%, (to about 420 vegetable-equivalent kilograms per person per year).

Cellier 2019 can be executed interactively under *SystemModeler* or invoked from *Mathematica* (Wolfram 2022). The combined *Mathematica* and *SystemModeler* framework renders *World3* extensible (i.e., the framework provides read and write access to *World3*'s data structures, model-execution control, extensive visualization functionality, and support ports of applications written in the *Mathematica* framework to the C++ language).[3]

1.2 High-level structure of *World3*

Software engineering distinguishes a purely conceptual representation of the structure a software system S from a representation of the structure of a physical implementation of S. In the vocabulary of software engineering, a purely conceptual representation of S is called a *logical* representation of S. A representation of a physical implementation of S describes how the concepts of the logical representation of S are realized in specific computer languages (together with hardware and human activities). In general, the mapping between the logical and physical representation of S can be many-to-many. (See Piccinini 2015 for a critical survey of issues arising from the logical/physical distinction.)

The theory and logical design (Boehm 1981, Section 5.4; Boehm et al 2000, 312-313) of *World3* can be found in Meadows et al. 1974. Much of the detailed physical design (Boehm 1981, Section 5.4; Boehm et al. 2000, 312-313) of Cellier 2019 can be found in the online documentation that accompanies Cellier 2019.

The high-level state variables of the logical structure of *World3* are population, pollution, agriculture, capital, and non-renewable resources. In *World3*, these variables are variously interdependent. Figure 1 shows a Level 1 dataflow diagram (DeMarco 1978) of the logical structure of *World3*. Note that there is a natural one-to-one correspondence between the high-level state variables of *World3* and the processes in the dataflow diagram.[4]

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[3] The combined *Mathematica*/*SystemModeler*/*World3* framework is characterized as "experimental" by the *Mathematica* v13.1 documentation (Wolfram 2022).

[4] A dataflow diagram depicts the movement of data between logical data transforms in a system. In such a diagram, an ellipse represents a data transform. An arrow represents a dataflow path: data flows from a source located at the tail of the arrow to an entity at the head of the arrow. Dataflow diagrams do not depict conditionality. In a fully articulated dataflow diagram, the arrows are labeled with the names of data, and the data are defined in a data dictionary.

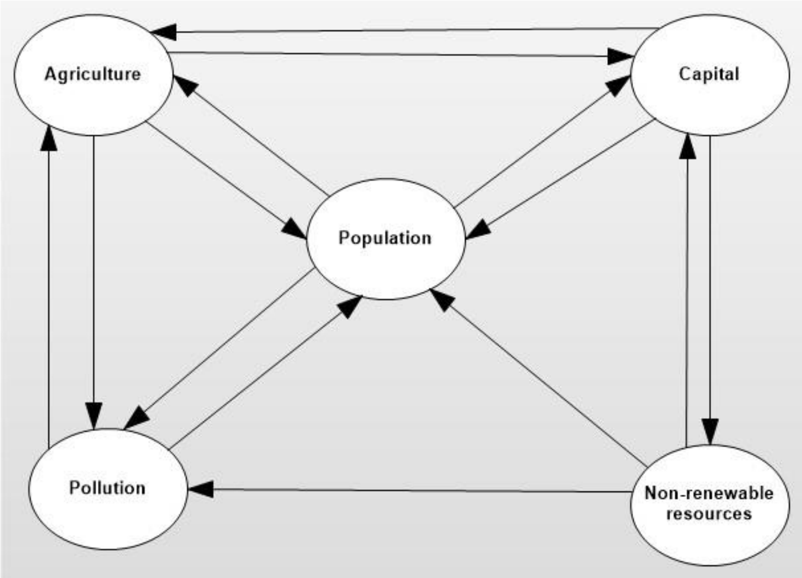

Figure 1. The Level 1 dataflow diagram (DeMarco 1978) of *World3*.

1.3 The *World3* Benchmark Scenarios

Meadows, Randers, and Meadows 2004 describe, at a high level, nine *World3* scenarios that span regimes ranging from continuing the practices and policies of the 20th century (called the "Business as Usual" scenario (BAU; see description below for further detail), to a sequence of scenarios that increasingly diverges from the BAU through increasing:

a. birth control and pollution controls
b. industrial and agricultural investment
c. food production technology
d. resource conservation practices
e. resource extraction efficiency

I will call these Scenarios "the *World3* Benchmark Scenarios" or "the Benchmark Scenarios".[5] Collectively, the Benchmark Scenarios provide a de facto baseline for analyzing the sensitivity of

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[5] Which *World3* scenarios should be subsumed under the name "Benchmark" could be debated, but it's clear enough that the community of *World3* users has found the nine nominated as "Benchmark" in this paper to be a convenient reference. Meadows, Randers, and Meadows 2004 describe a 10th scenario, which is Scenario 9 with the sustainability policies of Scenario 9 introduced 20 years earlier. The 10th scenario of Meadows, Randers, and Meadows 2004 is not included in the current study. Cellier 2019 includes a 10th and 11th scenario, neither of which identical to any of Scenarios 1-9. As implemented, in the *SystemModeler* framework, however, Scenarios 10 and 11 of Cellier 2019, will not compile on the platform described in Section 2 of this paper. For this reason, they were excluded from consideration in the present paper.

World3 predictions to variations in *World3* parameters.[6] By default, the duration of each Benchmark Scenario spans simulated calendar years 1900 - 2100.[7] Here is a high-level description of the trajectories produced by the Benchmark Scenarios (details of these scenarios can be found in Meadows et al. 1974; Meadows, Randers, and Meadows 2004; Cellier 2019).[8]

Benchmark Scenario 1 (the "business-as-usual" (BAU), scenario) (Meadows, Randers, and Meadows 2004, 168-171)**)**. In Scenario 1, human practices and policies continue without significant deviation from the those followed during most of the 20th century. As a result, population and production increases until growth is halted by increasingly inaccessible resources. Increasing investment is required to maintain resource flows. That investment, which must be re-directed from other sectors of the economy, leads to declining output of both industrial goods and services. The decline of industrial goods and services causes a reduction in the food supply and in health services, thereby decreasing life expectancy, resulting in a population "collapse" (nominally, a 50% reduction of population size in less than ~50 years) beginning calendar year 2040. Figure 2 shows population as a function of time in *World3* Benchmark Scenario 1. Figure 3 shows life expectancy as a function of time in that Scenario. Figure 4 shows food produced per capita as a function of time in that Scenario.

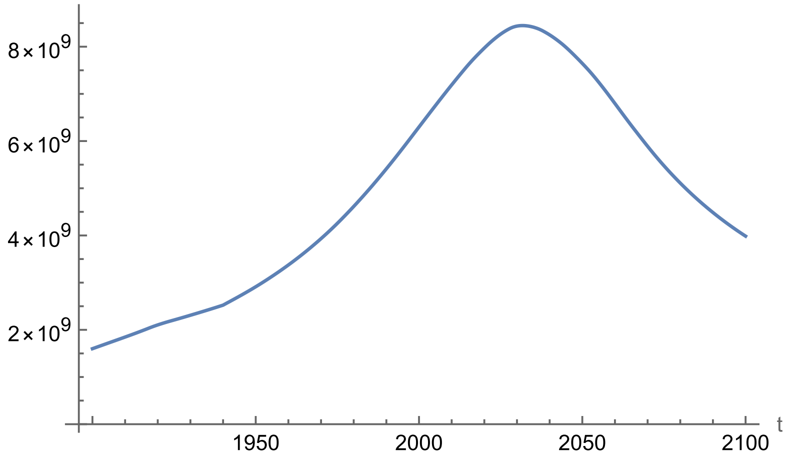

Figure 2. World population (number of persons) by time (Year). *World3*, Benchmark Scenario 1 ("Business as Usual").

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[6] Unless otherwise noted, the term "parameter" in this paper means a software entity whose value is user-settable and is kept constant for the duration of any given execution of a scenario.
[7] Some *World3* predictions for Years later than 2100 likely lie well outside the calibration space of the simulator.
[8] The Benchmark Scenario narratives in this Section closely follow those of Meadows, Randers, and Meadows 2004. Those narratives largely presume a causal idiom. A causal idiom presupposes the absence of feedback loops (Reichenbach 1958, pp. 136-137). *World3*, however, has several feedback loops (Meadows et al. 1974), so its behavior, strictly speaking, can be described only in joint-variation terms.

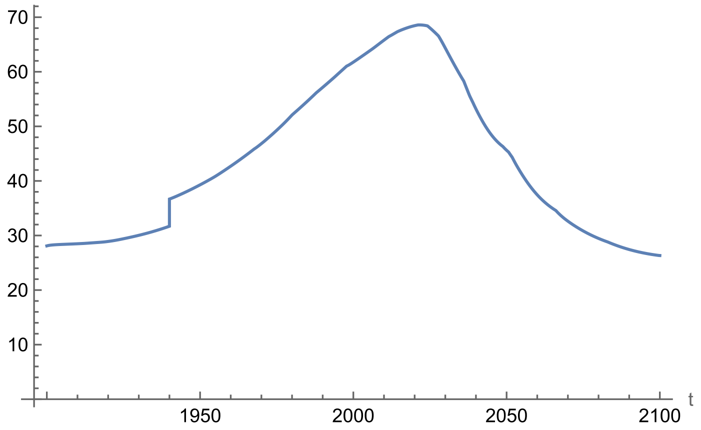

Figure 3. World average Life Expectancy (in years) by time (Year). *World3*, Benchmark Scenario 1.

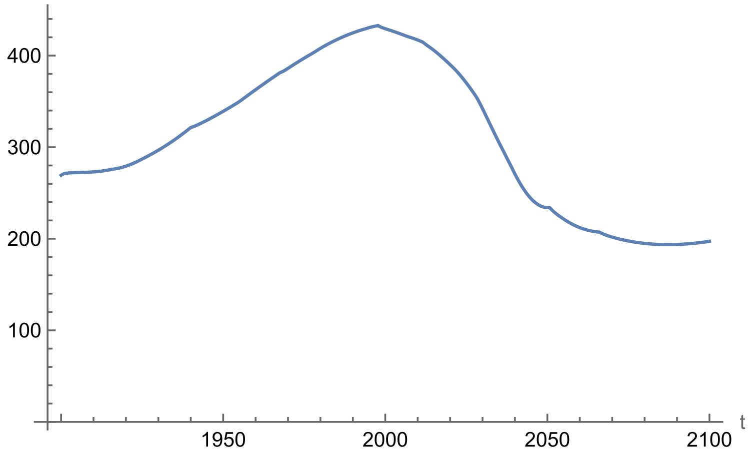

Figure 4. World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al. 1974, p. 64 for a definition of this term)) by time (Year). *World3*, Benchmark Scenario 1.

Benchmark Scenario 2 (Meadows, Randers, and Meadows 2004, 172-174). In this scenario, the nonrenewable resources assumed in Scenario 1 are doubled. Scenario 2 further postulates that advances in resource extraction technology postpone the onset of increasing extraction costs, thus allowing industry to grow 20 years longer than in Scenario 1. But as a consequence, pollution levels rise sharply, depressing land yields and requiring massive investments in agricultural recovery. The population finally declines because of food shortages and the health effects of pollution.

Benchmark Scenario 3 (Meadows, Randers, and Meadows 2004, 210-214). This scenario assumes the nonrenewable resource supply and extraction technologies assumed in Scenario 2. It also assumes increasingly effective pollution control technology that reduces the amount of pollution generated per unit of output by up to 4 percent per year, starting in 2002. This allows much higher welfare for more people after 2040 because of fewer negative effects of pollution. But food production ultimately declines, drawing capital from the industrial sector and triggering a population collapse.

Benchmark Scenario 4 (Meadows, Randers, and Meadows 2004, 214-216). This scenario adds to the pollution control technology of Scenario 3 and a set of technologies that greatly increase the food yield per unit of land. As a consequence, agricultural activities sharply increase the land loss rate. This scenario ultimately leads to a population collapse.

Benchmark Scenario 5 (Meadows, Randers, and Meadows 2004, 216-218). This scenario assumes more accessible nonrenewable resources, a better land-preservation technology than Scenario 4, and the pollution-reducing technology of Scenario 4. This only slightly postpones the population collapse to near the end of the 21st century.

Benchmark Scenario 6 (Meadows, Randers, and Meadows 2004, 218-220). This scenario assumes the world develops even more powerful pollution abatement and land protection than Scenario 5, and further assumes conservation of nonrenewable resources. All these technologies have costs and take 20 years to be fully implemented. In combination, they yield a fairly large and prosperous population until the accumulated cost of the technologies becomes unsustainable, ending in a population collapse.

Benchmark Scenario 7 (Meadows, Randers, and Meadows 2004, 238-241). This scenario assumes that after 2002 all families are limited to two children. Because of the age-structure momentum, however, the population continues to grow for another generation. The slower population growth permits industrial output to rise, until it is stopped by the cost of dealing with rising pollution (as in Scenario 2).

Benchmark Scenario 8 (Meadows, Randers, and Meadows 2004, 241-244). This scenario assumes that after 2002 families are limited to two children. The scenario sets a fixed goal for industrial output per capita. As a result, there is a "golden period" of fairly high human welfare between 2020 and 2040. But rising pollution increasingly stresses agricultural resources. Per capita food production falls, eventually degrading life expectancy and population.

Benchmark Scenario 9 (Meadows, Randers, and Meadows 2004, 244-247). In this scenario, population and industrial output are limited as in Scenario 8. In addition, technologies are added to aggressively abate pollution, conserve resources, increase land yield, and protect agricultural land. As a consequence, the planet's 8 billion people enjoy a high standard of living, and the human ecological footprint continuously declines. Figure 5 shows population as a function of time in *World3* Benchmark Scenario 9. Figure 6 shows life expectancy as a function of time in Scenario 9. Figure 7 shows food produced per capita as a function of time in Scenario 9.

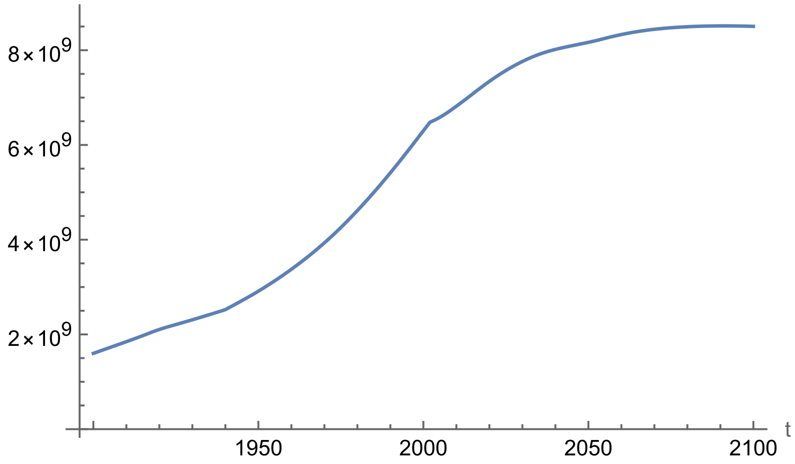

Figure 5. World population (number of persons) vs. time (Year). *World3*, Benchmark Scenario 9.

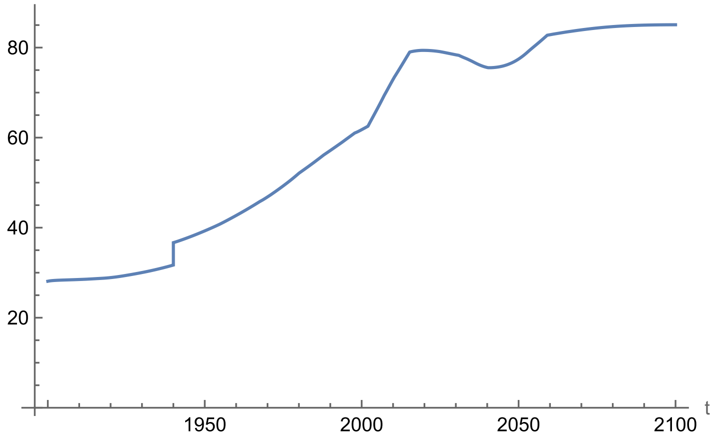

Figure 6. World average Life Expectancy (years) by time (Year). *World3*, Benchmark Scenario 9.

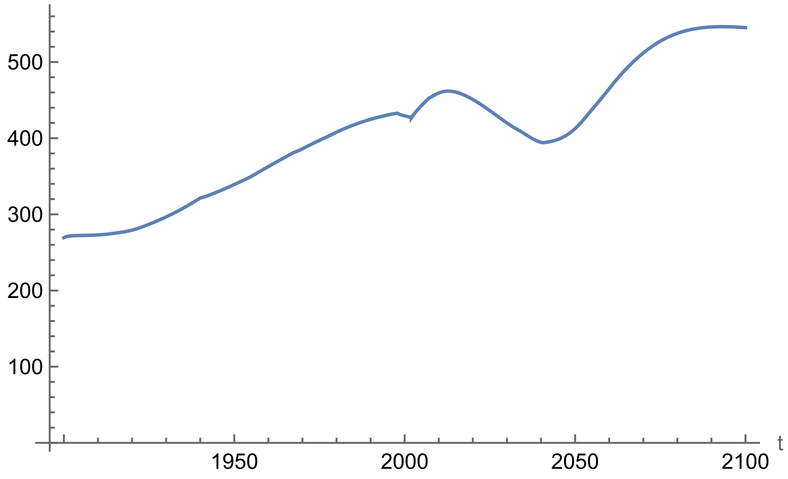

Figure 7. World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al. 1974), p. 64 for a definition), by time. *World3*, Benchmark Scenario 9.

In each of Benchmark Scenarios 1-8, population growth overruns the global carrying capacity of at least one resource, leading to a population collapse by Year 2100. Only in Benchmark Scenario 9 is such a collapse avoided.[9]

2.0 Method

The version of *World3* used in this study is Cellier 2019 hosted under the Wolfram 2019/Wolfram 2022 framework. *Modelica* v3.2.2 and v3.2.3 provided the *Modelica* resources required by Cellier 2019.[10] Microsoft C++ Visual Studio provided the C++ resources required by Wolfram 2019. All software used in this study was executed under Windows 10 on a Dell Inspiron 545 desktop containing an Intel Q8200 quadprocessor clocked at 2.33 GHz and 8 GB of physical memory.

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[9] The values of a few initial conditions and parameter values in the Benchmark Scenarios as described in Cellier 2019 differ slightly from those in Meadows et al. 1974. These differences are the result of a calibration of *World3* that occurred between about 1975 and 2008. The differences between the predictions of the Baseline Scenarios in Meadows et al. 1974 and the corresponding Benchmark Scenarios in Cellier 2019 that arise from the differences in the initial conditions and parameter values in Meadows et al. 1974 and Cellier 2019 are minor.

[10] If Cellier 2019 is executed interactively from *SystemModeler* (v12.0), the software used in this study produces an advisory (not an error) message stating that by default, it expects to use *Modelica* v3.2.1, but finds and uses *Modelica* v3.2.2 instead. If the software used in this study is executed under *Mathematica* (v13.1), *Mathematica* produces an advisory message stating that *Modelica* v3.2.3 is used. I am not aware of any differences (for the purposes of this study) among the results produced by *Modelica* v3.2.1, v3.2.2, and v3.2.3.

2.1 Selection of parameters to vary

Two criteria of adequacy must be satisfied in order to evaluate the sensitivity of a quantity, Y, to another quantity, X, in a given simulation/model M. Assume X' is a proxy for X. Then

A1. In M, we vary X (or X') and observe the effect of that variation on Y.

A2. The values of all *independent* variables and parameters in M other than X(or X') are kept constant.

When "sensitivity analysis" is used in the sense of A1-A2, the analysis does not address whether M "correctly" represents the world per se. Strictly speaking, a sensitivity analysis is instead concerned with the question how, within M, Y varies with X(X').[11]

As noted above, *World3* does not model explicitly pandemic modalities as such. *World3* contains, however, a parameter, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv,** that models the effect of health services on **Life Expectancy.**

In particular, in *World3* Life Expectancy, LE, is calculated as

$$LE = LN*LMF*LMHS*LMP*LMC \qquad \text{Eq. 1}$$

where

LN is "Normal Life Expectancy"
LMF is "Lifetime Multiplier from Food"
LMHS is "Lifetime Multiplier from Health Services"
  (called **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** in Cellier 2019)
LMP is "Lifetime Multiplier from Pollution"
LMC is "Lifetime Multiplier from Crowding"
* means multiplication

See Meadows et al. 1974 and Cellier 2019 for definitions of these terms.

The "effect of health services" is such only with respect to health contexts. Health contexts include pandemics. We would expect a pandemic satisfying (a)-(c) of Section 1.0 to reduce the effectiveness of health services that would otherwise obtain. Here I use this relationship to model the interaction of hypothetical pandemics that satisfy (a) - (c) in Section 1.0, with

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[11] Following IEEE 2011, I distinguish "verification", which concerns a satisfaction relation between a software system S and its specification, from "validation", which concerns the relationship between the specification and something (naively, the "real world") that is independent of the specification and software.

population/resource dynamics. In particular, I model the *effect* of such pandemics on ~200[12] *World3* variables by analyzing the sensitivity of those variables to a ±10% variation in the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv.** The choice of ±10% bounds on the variation of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** is broadly consistent with estimates of the global mortality rates in the 1918 influenza pandemic (Spreeuwenberg, Kroneman, and Paget 2019; ~3%), in the bubonic plague in urban areas in the Middle Ages (Christakos et al. 2005; ~50%), and in the COVID-19 pandemic (Johns Hopkins University 2022; ~0.1%).

Life Expectancy can be viewed proxy for death-rate and thus conceptually includes deaths caused by pandemics. We can derive this relationship in *World3* terms explicitly. In *World3*, the number of deaths per year (DPY) is expressed as the total number of persons in the population (POP) divided by the average Life Expectancy (LE) (Meadows et al. 1974, p. 58), i.e.,

$$\mathrm{DPY} = \mathrm{POP} / \mathrm{LE}. \qquad \text{Eq. 2}$$[13]

Deaths Per Capita Per Year (DPCPY) is therefore

$$\mathrm{DPCPY} = \mathrm{DPY} / \mathrm{POP} = 1 / \mathrm{LE}. \qquad \text{Eq. 3}$$

From Eq. 3 it follows that

$$\mathrm{LE} = 1 / \mathrm{DPCPY}. \qquad \text{Eq. 4}$$

LE, that is, is a proxy for (the inverse of) DPCPY.

In *World3*, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** is implemented in two tables, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1,** and **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. The default values of these two tables in Benchmark Scenario 1 are shown in Figures 8 and 9.

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[12] The Wolfram 2019 instruction *simulator_name***["Summary"]** reports that the *World3* Benchmark Scenarios each have 265 variables, where *simulator_name* is the name of a simulator object-variable recognized by Wolfram 2019. In one sense, any execution of a Benchmark Scenario (explicitly or implicitly) tests the sensitivity of all those variables to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. In the present study, the Wolfram 2019 instruction **SystemModelSimulateSensitivity** was used to analyze the sensitivity of all variables recognized by **SystemModelSimulateSensitivity** to be sensitive to each of the seven values of parameter **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.** For a list of these variables, see the instruction

```
simsensdata["SensitivityNames"]
```

in Horner 2022.

[13] Strictly speaking, this relationship is correct only for a theoretical stationary population (Keyfitz 1971, pp. 658-659)

In Benchmark Scenario 1, *World3* uses the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1** until the scenario time equals approximately 1940. For scenario times greater than about 1940, Benchmark 1 uses the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** defined in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**.[14]

{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[1] → 1}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[2] → 1.1}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[3] → 1.4}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[4] → 1.6}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[5] → 1.7}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[6] → 1.8}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[7] → 1.8}

Figure 8. Default values of Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1. Benchmark Scenario 1 uses these values of Life_Expectancy1.Lifet_Mlt_Hlth_Serv prior to scenario Year 1940.

{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] → 1}
Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[2] → 1.5}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[3] → 1.9}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[4] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[5] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[6] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[7] → 2}

Figure 9. Default values of Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2. Benchmark Scenario 1 uses these values of Life_Expectancy1.Lifet_Mlt_Hlth_Serv at or later than scenario Year 1940.

To summarize, by varying the (i.e., Benchmark Scenario-) values of parameter **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2** by ±10%, on the platform described above, we can approximate the effect, on ~200 *World3* variables, of a pandemic that satisfies the constraints identified in (a)-(c) of Section 1.[15]

The sensitivity of those *World3* variables to that variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals** was computed and plotted on the platform described in Section 2.0.

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[14] Although the switch from the values shown in Figure 8 to the values shown in Figure 9 may seem somewhat artificial, it is the result of a conscious decision by the developers of *World3* to reflect the fact that health services improved rapidly after 1940 (Meadows et al. 1974, pp. 75-76).

[15] See Section 4.2 for a brief discussion of tradeoffs among various approaches to modeling pandemics “within” the *World3* framework.

3.0 Results

The source code and results described in Section 2.0 were saved to a PDF file, accessible at Horner 2022. The collective wall-clock time for these calculations on the platform described in Section 2.0 was approximately 3 hours.

4.0 Discussion and conclusions

The results of the study merit several observations.

4.1 Study-specific observations

1. In Benchmark Scenarios 1-8, population/resource dynamics are strongly dominated by population growth overshooting the global supply of various resources, resulting in a population peak followed by a population crash (see, for example, Figure 2). In its simplest form, this behavior is the classic Malthusian catastrophe (Malthus 1798; Ehrlich and Ehrlich 2009): any resource required to sustain a population level must increase at least as fast as the population does, or the population will overshoot the carrying capacity of the resource and the population will collapse. In the presence of adequate resources, population tends to increase exponentially but the resources required to sustain that population tend to increase at best linearly. Over at least the last century, the global population has tended to grow at least one percent year over year (i.e., has exhibited an exponential growth rate of at least one percent per year), while agricultural output has, on average, exhibited only a linear growth rate.
2. Several of the population/resource variables in *World3* vary with **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2** as a function of time. Figure 10 shows an example of this behavior. The green curve corresponds to a +10% increase in the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].** The blue curve corresponds to the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].** The orange curve corresponds to a 10% decrease in the nominal value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].**

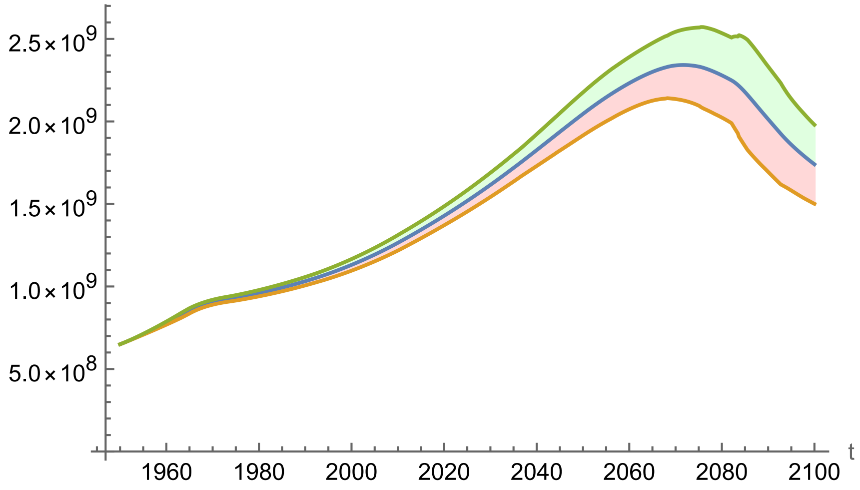

Figure 10. World population, age 0-14 years, as a function of time, given +/- 10% variation in Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1] in **Benchmark Scenario 1 ("BAU").**

3. Compared to the sensitivity of the *World3* variables in Benchmark Scenarios 1-8 to variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**, the corresponding variables in Benchmark Scenario 9 exhibit distinctive stability in the presence of variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. Figures 11-16 illustrate this stability by comparing the sensitivity of three *World3* variables (**Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y**, **Food_Production1.Agr_Inp.Integrator1.y**, and **Labor_Utilization1.Labor_Util_Fr_Del.Integrator1.y**, respectively) to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2** in Scenarios 1 and 9. In each of Figures 11-16 the green curve corresponds to a +10% increase in the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].** The blue curve corresponds to the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].** The orange curve corresponds to a 10% decrease in the nominal value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1].**

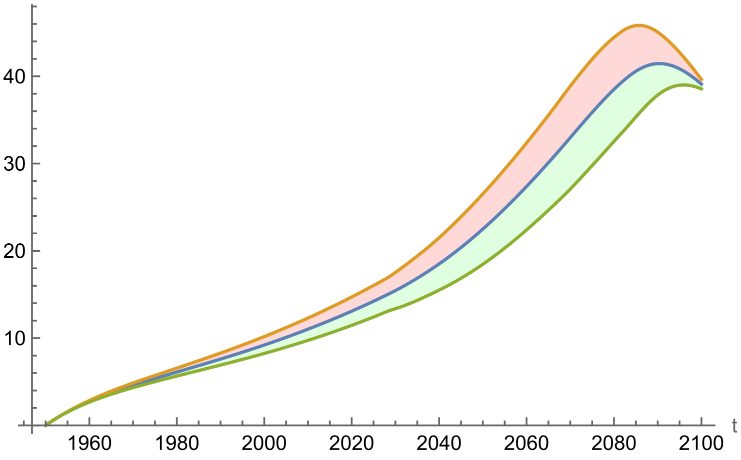

Figure 11. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 1.

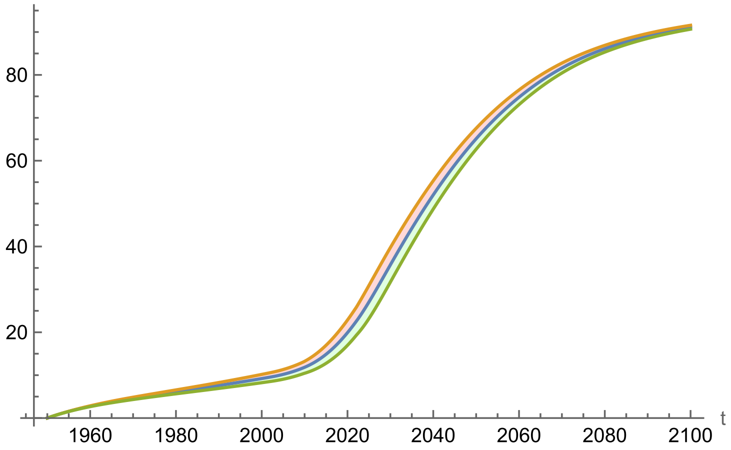

Figure 12. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 9.

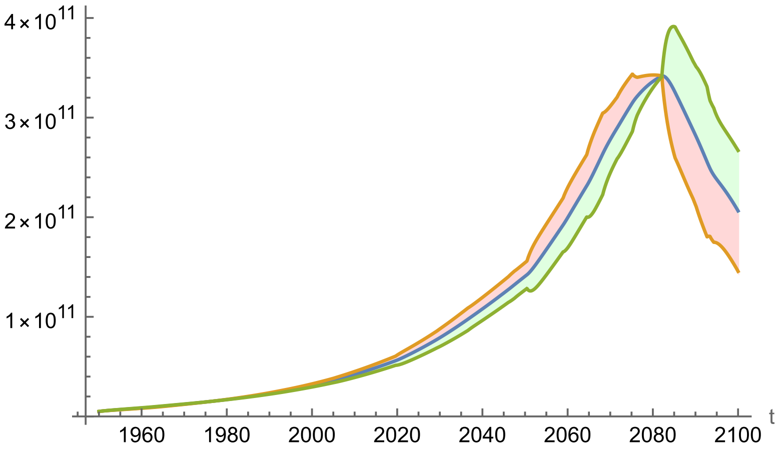

Figure 13. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 1.

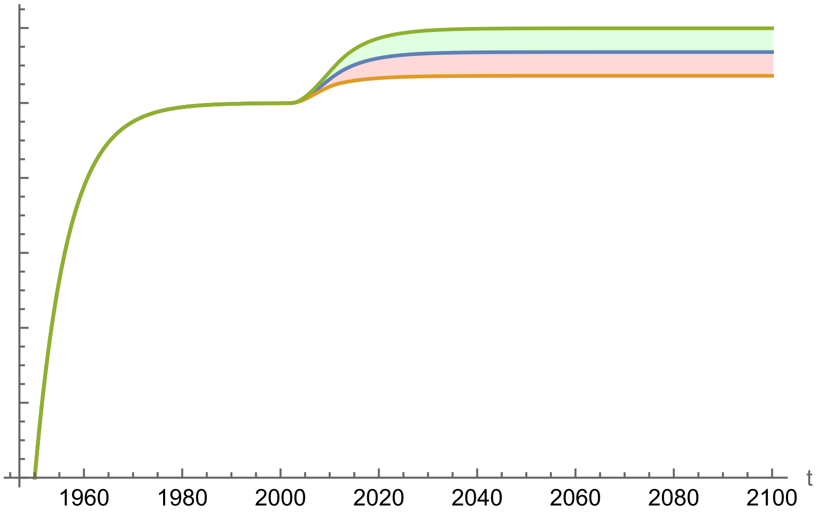

Figure 14. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 9.

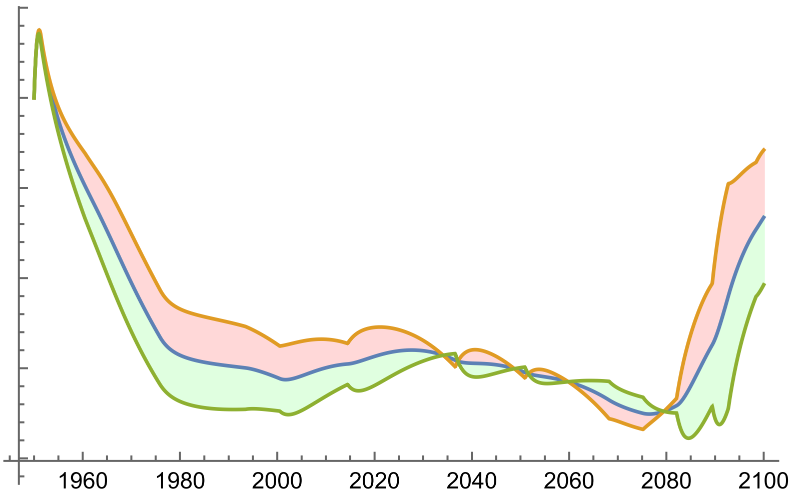

Figure 15. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 1.

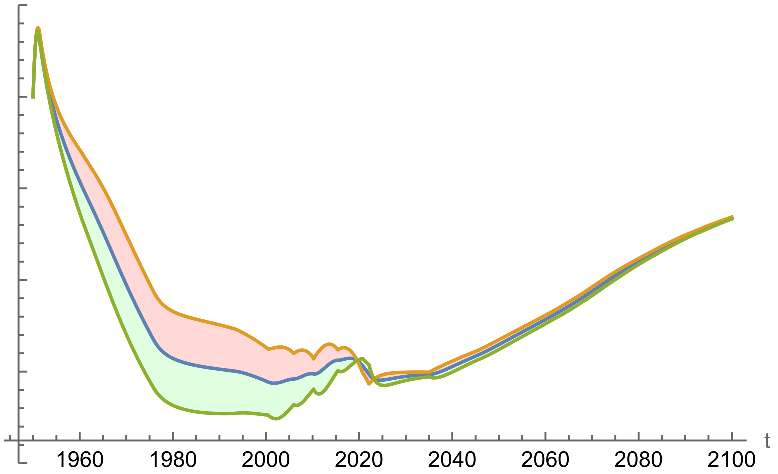

Figure 16. Sensitivity of Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y to Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] in Benchmark Scenario 9.

The results shown in Figures 11-16, together with Horner 2022, suggest that the population/resource-management policies and practices of *World3*'s Benchmark Scenario 9 can strongly mitigate the fiscal and physical disruption of a pandemic satisfying (a)-(c) of Section 1.0.

> One way of understanding the latter result is to note that resource demand/consumption rate in *World3* is effectively linear in population size. In Benchmark Scenarios 1-8, therefore, exponential population growth drives exponentially increasing demand for resources. In Benchmark Scenario 9, in contrast, population growth goes to zero and all resources required to sustain the population are renewable at the rate they are consumed. This approximates an equilibrium regime (Voit 2000, esp. pp. 417-421; Apostol 1967, Chap. 7).

See Horner 2022 for further details.

4.2 General observations

1. There are limits to using *World3* to help probe the interaction of human population dynamics and pandemic dynamics. For example, the effects of pandemics on population/resource dynamics might lie outside what *World3* per se can plausibly represent. If so, using *World3* to help bound estimates of the interaction of pandemic, and human population, dynamics could cause us to seriously mis-estimate that interaction.

   Though well taken, it should be noted that this kind of concern is not unique to *World3*, or even to simulation-based estimation: it applies to *all* ampliative (non-deductive) inferences (Salmon 1967, 8-12) that have not been, or for various pragmatic reasons (e.g., ethical, financial, technological) cannot be, exhaustively tested. This limitation is inherent in all empirical science (see, for example, Hume 1739, Book I, Part III; Salmon 1967; Symons, Boschetti, Fulton, and Bradbury 2012; Winsberg 2010; Symons and Alvarado 2019).

2. It has been argued by several *World3* critics that technological changes could render *World3*'s sobering predictions moot. Increases in agricultural productivity, one variant of that argument goes, could solve the predicted food shortage problem (see, for example, Simon 1996, esp. Chap. 6). Let's call the class of arguments that assert that technological changes could render World3's predictions moot "technological change" arguments.

   This argument, though seemingly plausible, is deeply problematic. It is simply not true that the *World3* Benchmark Scenarios do not consider technological change. Each of Benchmark Scenarios 2-9 implicitly hypothesize technological changes (including increased food productivity in particular) with respect to Benchmark Scenario 1 (BAU). Benchmark Scenario 9, moreover, outlines the scope of technological changes that could prevent the population-collapse problem.

Some “technological change” arguments do not specify which technological changes would render *World3*’s predictions moot. Such formulations are not testable even in principle, raising the question of whether those formulations are part of empirical science (for a discussion of this class of problems, see Hempel 1965, pp. 3-4; Quine 1961, esp. Section 6).

3. Models that integrate the interaction of population/resource-, with pandemic-, dynamics are inherently high-dimensional, and as a consequence using them might seem to entrain an intractable calibration problem. Though this concern is not to be taken lightly, the Central Limit Theorem (Chung 2001, esp. Chap. 7) ensures that for large randomly generated ensembles, Monte Carlo estimates of dynamics (Liu 2001) converge. (“Convergence” in this sense is a necessary, but not a sufficient, condition for “convergence to ‘real-world’ scenarios”.) We could, in particular, use *World3* as the ensemble-generator in a Monte Carlo simulation.[16]

4. Maximum entropy techniques (Jaynes 1988; Kapur and Kesavan 1992; Cover and Thomas 1991, esp. Chap. 12; Newman 2010, esp. Chap. 15) could be used to estimate expected values of *World3* metrics.

5. One could explicitly add a compartmental epidemiological model such as SEIRD to the baseline *World3* code. Implementing modifications to the *World3* code, however, would require introducing additional independent parameters or variables. There are tradeoffs between introducing those complexities on the one hand vs. appropriating -- where possible -- the semantics of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. It could be argued, for example, that re-purposing the indicated parameters “overloads” the default intended semantics of those parameters. (“Intended semantics” in this sense is not determined by software and hardware per se, but by a relationship between software and hardware on the one hand, and intentions implied by the system specification on the other hand (Turner 2011).) All other considerations being the same, semantic overloading of program elements can increase software and conceptual complexity and thereby increase the risk of programming or usage errors (see, for example, Ullman 1988, esp. Chap. 7; Aho, Hopcroft, and Ullman 1983, esp. Section 1.6; Booch and Bryan 1993; Parnas 1972). Against this, it can be argued that at least some kinds of semantic overloading allow us to aggregate similar items better than alternative approaches; indeed, some modern programming languages (e.g., ISO/IEC 2017; MITRE Corporation 2000) have fundamental syntactic and semantic resources to regiment such overloading.

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[16] A Monte Carlo approach to the general topic of this paper would require at least tera-scale computing resources to produce results in a time anyone would be willing to wait.

Not least, adding new variables or parameters to *World3* would introduce variant versions of the *World3* software, and thus would increase the complexity of *World3*'s executable-code configuration management and calibration spaces (Leon 2015). Changing the values of parameters in a software system, of course, introduces data-configuration management issues in its own right (Symons and Alvarado 2016).

In short, any approach to the problem of extending a given simulator involves tradeoffs.

6. A parameter-variation technique analogous to the one used in the study could be used to analyze the effect of CO_2-induced temperature increases on agricultural production. More specifically, *World3* does not explicitly model greenhouse-gas (GHG) effects directly, but it does parametrically model the effect of "persistent pollution" on agricultural production in a way that appears to be amenable to the variation of parameters method used in the present study. Future work will pursue this conjecture.

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This work benefited from discussions with Toufiq Siddiqi, Jorge Soberón, John Symons, Ramón Alvarado, Anthony Pawlicki, Richard Stutzke, and Richard Frank. Not least, the paper benefited greatly from recommendations from reviewers. For any infelicities that remain, I am solely responsible.

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