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A *World3* analysis of the response of population-resource dynamics to age-cohort-specific variation in pandemic-scale mortality

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Abstract

Every known mortality-producing pandemic to date exhibits wide mortality variation among age-cohorts. Such variation could be expected to induce non-uniform effects on population/resource dynamics. To help probe those effects, I used a well-characterized population-resource dynamics simulator, *World3*, to compute the response of the five *World3* population-resource "sectors" (i.e., population, agriculture, capital, non-renewable resources, and pollution, as those sectors are represented in the structure and assumptions of *World3*) to age-cohort-specific variation in pandemic-scale mortality, in nine World3 Benchmark Scenarios, ranging from the practices of the 20th century to a sequence of scenarios that implement birth control and pollution controls, increase industrial and agricultural investment, and improve food production technology, resource conservation practices, and resource extraction efficiency. The results show that in all but one Benchmark Scenario, 60% or more of *World3*'s sectors are sensitive to age-cohort-specific variation in mortality, in several sectors for more than 30 years (i.e., a nominal human generation).

Keywords: Population/Resource Dynamics; Pandemic Mortality; Global Resource Management; *World3*

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1. Introduction

Every known mortality-producing pandemic to date has exhibited wide mortality variation among age-cohorts. Such variation could be expected to induce non-uniform effects on population/resource dynamics. Horner (2022) provides a *World3* (Meadows et al., 1974; Cellier, 2019; Bardi and Pereira, 2022; Nebel et al., 2023) analysis of the sensitivity of population/resource dynamics to pandemic-scale variation in total-population life expectancy (equivalently, to total-population mortality). As such, the results of Horner (2022) do not directly address the question of whether there are *World3* age-cohort-specific life-expectancy/mortality sensitivities in the regimes of interest. The present paper describes an analysis of the sensitivity of *World3* population-resource dynamics to age-cohort-specific variation in pandemic-scale mortality.

Strictly speaking, this paper concerns the behavior of the *World3* simulator proper, under a specific range of variation of a specific *World3* parameter. Predictions obtained from the simulator experiments described in the paper are *hypotheses* that could, at least in principle, be empirically tested.

2. Overview of *World3*

The *World3* simulator (Meadows et al., 1974; Cellier, 2008; Cellier, 2019; Wolfram, 2019; Wolfram, 2025; Bardi and Pereira 2022; Nebel et al., 2023) is a software system of approximately 330 equations and 330 variables that model the dynamical interaction of what *World3* calls "sectors": world population, pollution, agriculture, capital, and non-renewable resources. Recent assessments (Turner, 2008; Turner, 2014; Randers, 2012; Nørgård et al., 2010; Herrington, 2020; Nebel et al., 2023; Bardi and Pereira, 2022) of *World3* have argued that, for calendar years 1900 to 2020, *World3* (especially Benchmark Scenario 1; see Section 2.1 below) predicts population, food production, and capital-dynamics magnitudes that are within 15% of actual ("real-world") values.

2.1. The *World3* benchmark scenarios

Meadows et al. (2004), Cellier (2019), Bardi and Pereira (2022), and Nebel et al. (2023) describe nine *World3* scenarios that span regimes ranging from continuing the practices and policies of the 20th century (called the "Business as Usual" scenario (BAU)), to a sequence of scenarios that increasingly diverges from the BAU through increasing:

- birth control and pollution controls
- industrial and agricultural investment
- food production technology
- resource conservation practices
- resource extraction efficiency

I will call these nine Scenarios "the *World3* Benchmark Scenarios" or "the Benchmark Scenarios". Collectively, the Benchmark Scenarios provide a de facto baseline for analyzing the response of *World3* predictions to variations in *World3* parameters and initial conditions. By default, the duration of each Benchmark Scenario spans simulated calendar years 1900 - 2100. Details of Benchmark Scenarios 1-9 can be found in Meadows et al. (1974), Meadows et al. (2004), Cellier (2019), Bardi and Pereira (2022), and Nebel et al. (2023).

In Benchmark Scenarios 1 – 8, population/resource dynamics are strongly dominated by population growth overshooting the global supply of various essential resources, resulting in a population peak followed by a population crash (nominally defined as a 50% reduction in population in 50 years or less). In its most rudimentary 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. Of the nine Benchmark Scenarios, only Benchmark Scenario 9 avoids a population collapse.

3. Method

This section describes the method used in the present study. Section 3.1 describes the platform used in the study. Section 3.2 identifies, and provides rationale for, the *World3* parameters that were varied in the study.

3.1. Platform

The version of *World3* used in this study is Cellier (2019), hosted under the *System Modeler/Mathematica* (Wolfram, 2019; Wolfram, 2025) framework. The configuration files for Benchmark Scenarios 1-9 are bundled with Cellier (2019). *Modelica* 4.0 (2025) provides the *Modelica* resources required by Cellier (2019). Cellier (2019) provides a detailed mapping between *World3*'s "sectors" and their *Modelica* implementation counterparts. Microsoft C++ Visual Studio provided the C++ resources required by Cellier (2019)), Wolfram (2019), and Wolfram (2025). 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. (It seems plausible that other platform configurations could produce the same results as the configuration used in this study, but whether they do was not investigated in this study.)

3.2. Selection of parameters to vary

The approach used in the present study to investigate the effects on population-resource dynamics, *within World3*, of age-cohort-specific variation in pandemic-scale mortality requires a set of parameters in *World3* that can at least bound the effects of interest. Although *World3* does not explicitly model pandemic dynamics per se, it is possible to appropriate *World3*'s parametric modeling of age-cohort-specific mortality to bound, within *World3*, the sensitivity of population/resource dynamics to age-cohort-specific mortality variation.

More specifically, *World3* contains a family of parameters, **Population_Dynamics1.Mort_xxxx.y_vals**, where xxxx = [0-14 | 15-44 | 54-64 | 65+], that defines mortality as a function of life expectancy for each of four age-cohorts (0-14 years, 15-44 years, 45-64 years, and 65 years or older). *SystemModeler* supplies a function, **SystemModelSimulateSensitivity**, that returns (among other things) the names of all *World3* variables that could be sensitive to variation in any given *World3* parameter**.** (What counts as a (*Modelica*) variable when **SystemModelSimulateSensitivity** is invoked can be selected through an optional **SystemModelSimulateSe nsitivity** argument. If the user does not explicitly specify a set of such variables in a **SystemModelSimula**

teSensitivity invocation, **SystemModelSimulateSensitivity** chooses the list of *Modelica* variables to analyze. The present study did not specify a set of variables for **SystemModelSimulateSensitivity** to analyze. The list of variables **SystemModelSimulateSensitivity** chose to analyze in the present study are shown in Horner 2025.)

SystemModeler also provides a powerful sensitivity analysis function, **SystemModelPlot**, which, given a parameter P, a *Modelica*_variable V, and a percent range R of variation of P, returns a plot of the sensitivity of V to variation in P over R. In this study, R was set to +/- 30% of the nominal value of the parameter of interest. There are three compelling reasons for choosing this value of R:

- In the Benchmark Scenarios, variation outside R involves trajectories that lie outside World3 calibration envelope.
- In some Benchmark Scenarios, a range of variation larger than R will cause World3 to abort on Modelica error-management code that helps to keep World3's numerical integrators stable.
- The mortality of most known pandemics lies within R. The 1918 influenza pandemic, for example, satisfied this constraint (Spreeuwenberg, Kroneman, and Paget, 2018), as did the COVID-19 pandemic as of August 2022 (Johns Hopkins University, 2022).

For each Benchmark Scenario, **SystemModelPlot** was applied to each (*Modelica*_variable, **Population_Dynamics1.Mort_xxxx.y_vals**) pair identified by **SystemModelSimulateSensitivity**, assuming a +/- 30% range of variation of **Population_Dynamics1.Mort_xxxx.y_vals.**

4. Results

SystemModelSimulateSensitivity identified 328 (*Modelica*_variable, **Population_Dynamics1.Mort_xxxx.y_vals**) pairs per Benchmark Scenario, yielding a total of 2952 (*Modelica*_variable, **Population_Dynamics1.Mort_xxxx.y_vals**) pairs whose sensitivity was then analyzed by **SystemModelPlot**. The results of that analysis are detailed in Horner (2025).

Figures 1 and 2 depict two of the 2952 sensitivity analyses generated by **SystemModelPlot** in this study. In each of Figures 1 and 2, the blue line corresponds to the effect of 1.0 times the nominal value of **Population_Dynamics1.mort_0_14.y_vals[2]** on the indicated *Modelica*_variable. The green line corresponds to the effect of 1.3 times the nominal value that parameter on the indicated *Modelica*_variable. The orange line corresponds to the effect of 0.7 times the nominal value that parameter on the indicated *Modelica*_variable.

Figure 1 is cast in terms of *World3*-specific (here, *Modelica*-variable-name) nomenclature. We can translate that nomenclature to terms that are more familiar to policy stakeholders. To put Figure 1 in context, recall from Section 2.1 that the overall objective of the Benchmark Scenario specifications is to find a scenario that will prevent a catastrophic population collapse in the latter half of the 21st century. Toward that end, Benchmark 4 (Meadows et al., 2004, pp. 214-216) adds significant pollution control technologies (to those of Benchmark Scenarios 1-3; see Meadows et al., 2004, pp. 168-214) that greatly increase the food yield per unit of land. **Population_Dynamics1.mort_0_14.y_vals[2]** represents mortality in the 0-14 year-old population cohort (Cellier, 2019). **Food_Production1.Agr_Inp.Integrator1.y** represents total agricultural investments (Cellier, 2019). As the world population increases, the pollution-mitigation investments that must be made to increase the food yield per unit of land to a level that will meet food consumption requirements becomes a dominant component of **Food_Production1.Agr_Inp.Integrator1.y.** Figure 1 shows that the pollution-mitigation investments in Benchmark Scenario 4 that are required to meet food demand will become acutely sensitive, from 2030 to about 2060, to variation in the mortality (in the case of interest, pandemic-induced mortality) in the 0-14-year old population cohort.

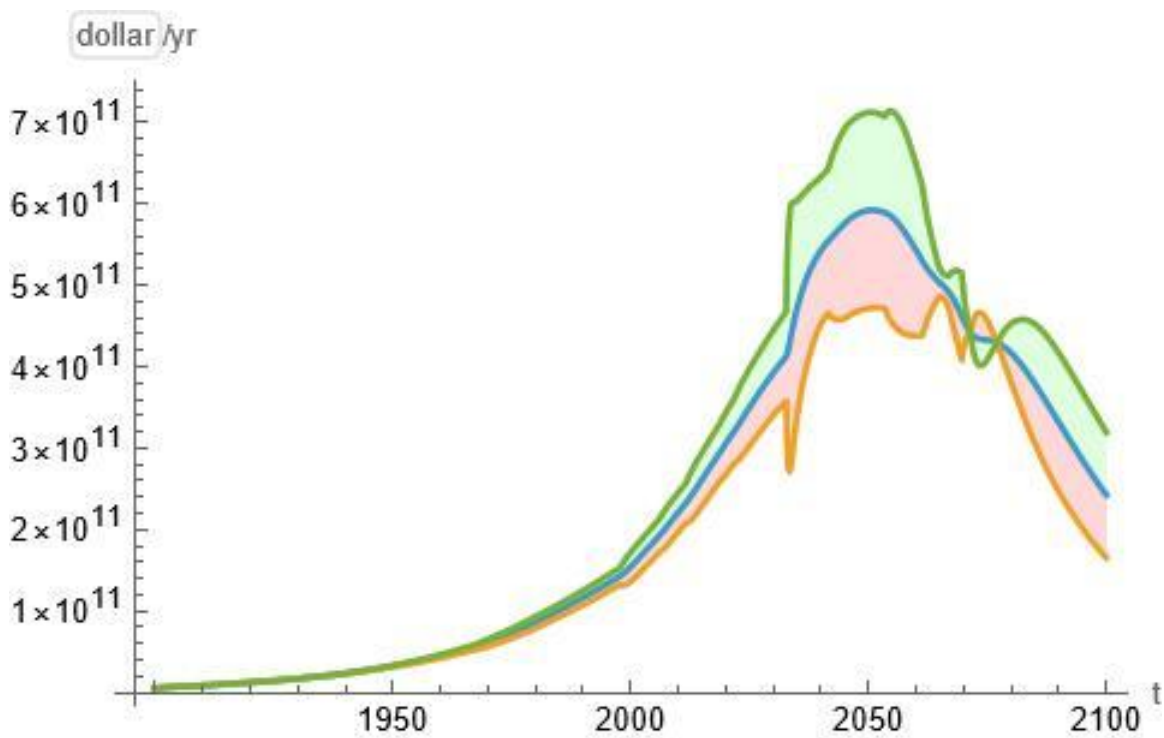

Figure 1. Benchmark Scenario 4. Sensitivity of variable Food_Production1.Agr_Inp.Integrator1.y to Population_Dynamics1.mort_0_14.y_vals[2].

This simulation result motivates a *consideration of tradeoffs* between investing in resources (such as health-management resources) to help mitigate the instabilities caused by variation in the mortality of the 0-14 year-old cohort on labor utilization, versus investing in (health-management) resources that mitigate variation in mortality in, say, the 65+ year-old cohort.

Deciding how to allocate investments in such a tradeoff regime involves ethical considerations that lie outside the scope of *World3*.

Like Figure 1, the implications of Figure 2 can be cast in terms that are more familiar to policy stakeholders. Figure 2, like Figure 1, assumes Benchmark Scenario 4. Variable **Labor_Utilization1.Labor_Util_Fr.Del. Integrator1.y** is a measure of the degree to which the labor force is occupied by the available jobs (Cellier, 2019; Meadows et al. 1974, p. 241). Consider Calendar Years 2060 – 2065, during which **Labor_Utilization1. Labor_Util_Fr.Del.Integrator1.y** exhibits relatively strong sensitivity to variation in **Population_Dynamics 1.Mort_0_14.yvals[2].** Figure 2 predicts that labor utilization (which includes unemployment rates and labor shortages) during those years will become relatively sensitive to variation in the mortality of the 0-14-year-old cohort.

As in the case of Figure 1, this simulation result motivates *consideration of tradeoffs* between investing in resources to help mitigate the instabilities caused by variation in the mortality of the 0-14-year-old cohort on labor utilization, versus investing in resources that mitigate variation in mortality in the 65+ year-old cohort on that utilization.

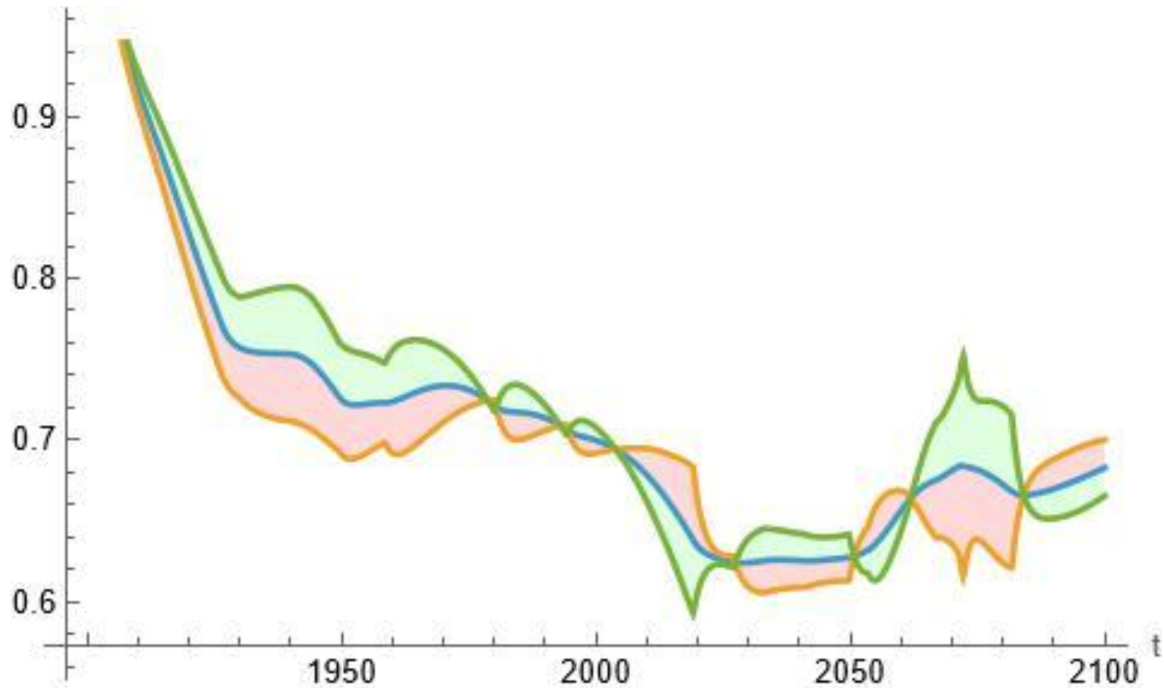

Figure 2. Benchmark Scenario 4. Sensitivity of variable Labor_Utilization1.Labor_Util_Fr.Del. Integrator1.y to Population_Dynamics1.Mort_0_14.yvals[2].

Figures 1 and 2, and the "policy-stakeholder"-language translations associated with those Figures, can be abstracted to a translation rubric for any **SystemModelPlot** sensitivity analysis of *World3*. In outline, that rubric is:

- Obtain the policy-stakeholder-language narrative from Meadows et al. (1974) for a given Benchmark Scenario S, S = 1, 2, …, 9 (for example, S = 4 denotes Benchmark Scenario 4).
- From Meadows et al. (1974), obtain policy-stakeholder-language translations of the *World3* variables in play in a given sensitivity graph G (e.g., Figure1) produced by SystemModelPlot.
- Interpret G in terms of the causal structure of World3 as depicted in Figure 1-3 (p. 14) of Meadows et al. (1974).

Table 1 summarizes those *World3* sectors that are associated, in the sense of Cellier (2019), with at least one *Modelica* variable whose sensitivity to variation in a Population_Dynamics1.Mort_xxxx.y_vals parameter is > 10% of the nominal value of that *Modelica* variable.

Table 1. World3 sectors that are associated, in the sense of Cellier (2019), with at least one Modelica variable whose sensitivity to variation in a Population_Dynamics1.Mort_xxxx.y_vals parameter is > 10% of the nominal value of that Modelica variable. Values shown are for the 0-14 year old cohort only (all other cohorts, in all Benchmark Scenarios, show smaller sensitivities). Note that the "Duration of Sensitivity" in many Sector/Scenario combinations spans multiple generations (i.e., > 30 years).

***World3* Sector**	**Benchmark Scenario Number**	**Duration of Sensitivity**
Agriculture	1	2000-2070
Population	1	1950-2090
Capital	1	1940-2100
Pollution	1	2030-2100
Agriculture	2	1930-2000
Population	2	1990-2100
Capital	2	1930-2100
Pollution	2	2020-2050
Agriculture	3	2030-2100
Population	3	1980-2100
Capital	3	2030-2100
Pollution	3	2010-2070
Agriculture	4	2010-2100
Population	4	2030-2060
Capital	4	2020-2100
Non-renewable Natural Resources	4	2050-2100
Pollution	4	2000-2060
Agriculture	5	2020-2100
Population	5	1970-2100
Capital	5	2070-2100
Non-renewable Natural Resources	5	2030-2080
Pollution	5	2010-2070
Agriculture	6	2010-2100
Population	6	2010-2100
Non-renewable Natural Resources	6	2000-2100
Pollution	6	2010-2070
Capital	6	2010-2100
Agriculture	7	1920-2100
Population	7	1960-2100
Capital	7	1930-2100
Pollution	7	2060-2090
Agriculture	8	1920-2010

World3 Sector	Benchmark Scenario Number	Duration of Sensitivity
Capital	8	1920-2100
Pollution	8	2040-2080
Population	9	2030-2100
Capital	9	1930-2010

Three general trends can be distilled from Table 1:

- In each Benchmark Scenario, variation in mortality in the 0-14 year old cohort has both larger and more diverse effects on *World3* sectors than any other age-cohort in the study.
- In each Benchmark Scenario, variation in parameter Population_Dynamics1.Mort_xxxx.y_vals[2] has a larger effect on World3 sectors than any of the other seven members of this family of parameters.
- Variation in mortality in the 0-14 year old cohort correlates strongly with variation in several sectors, especially with Agriculture.

The total wall-clock time to execute all 2952 sensitivity analyses documented in Horner 2025 was approximately 20 hours, corresponding to 10^{14} - 10^{15} machine-operations on the platform described in Section 3.1.

5. Discussion

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 et al. (2004) describe a 10th scenario, which is Benchmark Scenario 9 with the sustainability policies of Benchmark Scenario 9 introduced 20 years earlier. The 10th scenario of Meadows et al. (2004) is not included in the current study. Cellier (2019) includes a 10th and 11th scenario, neither of which identical to any of Benchmark 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 3.1 of this paper. For this reason, those two scenarios were excluded from further consideration.

As an alternative to the parameter-variation-based approach used in the present work, one could explicitly model the relation between age-cohorts and the sectors shown in Table 1 by modifying the *World3* software (e.g., by adding an explicit pandemic model). Such an approach, however, would not yield *World3* as such. The resulting software would therefore have to be calibrated and verified. The effort required to perform that calibration and verification would be at least as large as the effort expended by the *World3* user community to date to test and calibrate *World3* (thousands of person-years).

Result 3 in Section 4 (variation in mortality in the 0-14 year-old cohort at a given time T correlates strongly with variation in several sectors about 20 years later) is somewhat counterintuitive. Here's a plausible hypothesis about that result. Let T be Calendar Year 2030. Consider the 0-14 year-old cohort at T – 20 years (= Calendar Year 2010), whose mortality is given by **Population_Dynamics1.Mort_xxxx.y_vals[2]**. At T, the peak of exponential population growth is superposed on the entry, into the labor force, of what was the 0-14 year-old cohort at T – 20 years. That is, the labor force at T can be markedly diminished by pandemic mortality in the 0-14 year-old cohort at T – 20 years, just when (at T) the demand for resources (e.g., food) peaks.

The results summarized in Section 4 show that in all but one *World3* Benchmark Scenario, 60% or more of *World3*'s sectors (as defined within *World3* proper) are sensitive (in the sense defined in Section 3) to age-cohort-specific variation in mortality. The results further show that, in all *World3* Benchmark Scenarios, there are multi-generational (> 30 years) sector sensitivities in at least some pandemic-scale mortality regimes. Hypotheses, cast in policy-stakeholder terms, about any of the 2952 sensitivity analyses shown in Horner (2025) can be generated in accordance with the translation rubric shown in Section 4.

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