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A *World3* analysis of the response of population-system dynamics to climate-change-driven loss of wheat production

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Abstract

IPCC climate models that predict a 5 °C or greater increase in average global temperature (with respect to the average global temperature of the 20th century) will render the planet's principal wheat-growing regions significantly less productive than they are today. The effects of such a loss will include a profound decrease in food security through both direct and indirect population-dynamics pathways. To help investigate these effects, I use a well-characterized population-system dynamics simulator, World3, to compute the World3 response of 11 World3 population-system variables to a 0% - 30% loss of wheat production, in nine World3 "Benchmark Scenarios". These scenarios span regimes 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 strongly suggest that none of the Benchmark Scenarios can mitigate all of the population-system effects of wheat-production loss due to IPCC scenarios RCP4.5 and RCP8.5.

Keywords: *population/resource dynamics, wheat production, World3*

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1.0 Introduction

This paper describes a *World3*-based analysis (Meadows et al. 1974; Cellier 2019) of the response of population-system dynamics to climate-change-driven loss of wheat production. Section 2.0 provides an overview of *World3.* Section 3.0 describes the method used in this study. Section 4.0 reports the results of Section 3.0. Section 5.0 discusses how some common simulation issues relate to the study reported in this paper.

2.0 Overview of *World3*

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, and non-renewable resources. *World3*'s behavior is well understood ((Turner, 2014), (Herrington, 2020)). It evolved from the *Limits to Growth* project (Meadows et al., 1972), 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, p. 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 et al., 2010), (Herrington, 2020)), however, argue that *World3* (especially *World3*'s Benchmark Scenario 1; see Section 1.3 of this paper) has predicted the trajectories of the global population and food production well. Table 1 compares the population predictions of *World3*'s "Business as Usual" (BAU) scenario (see Scenario 1, Section 1.2) with UN estimates (United Nations, 2019) of the world population, 1980 to 2020.

Table 1. Comparison of some *World3*'s population predictions (from the "Business as Usual" (BAU) Benchmark Scenario; see Section 1.2) with the UN estimates (United Nations, 2019). Population is rounded to two significant figures; percent difference is rounded to one significant figure.

Year	*World3* prediction of world	UN estimate of world	Percent difference between

	population (billions, from BAU Scenario)	population (billions)	*World3* prediction, and UN estimate, relative to UN estimate
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.

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 kilograms per person per year.

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

[1] Meadows et al. (1974) estimate that 230 kilograms vegetable-equivalent production per capita per year (equivalent to 2200 kilocalories of vegetable-equivalent energy per person per day) is required for survival.

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

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 somewhat more pessimistic than UN estimates for 2010 and 2020. Herrington (2020) shows that current empirical data is broadly consistent with the *World3* projections, and that if major changes to the consumption of resources are not undertaken, *World3* predicts that 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 et al., 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 an adaptation of Cellier (2008) to the *System Modeler* (Wolfram, 2019) simulation framework.

The logical design (in the sense of (Boehm, 1981, Section 5.4), (Boehm et al., 2000, pp. 312-313)) of *World3* is described in Meadows et al. (1974). Much of the detailed physical design (in the sense of (Boehm, 1981, Section 5.4), (Boehm et al., 2000, pp. 312-313)) of Cellier (2019) is described in the online documentation that accompanies Cellier (2019).

Cellier (2019) can be executed interactively under Wolfram's *System Modeler* (Wolfram, 2019) or invoked from a *Mathematica* script (Wolfram, 2023). The combined *Mathematica* and *System Modeler* 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 supports ports of applications written in the *Mathematica* framework to the C++ language).[3]

2.2 The *World3* Benchmark Scenarios

Meadows et al. (2004) and Cellier (2019) 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), to a sequence of scenarios that increasingly diverges from the BAU through increasing:

a. birth control and pollution controls
b. industrial and agricultural investment

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

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".[4] Collectively, the Benchmark Scenarios provide a de facto baseline for analyzing the response of *World3* predictions to variations in *World3* parameters.[5] By default, the duration of each Benchmark Scenario spans simulated calendar years 1900 - 2100.[6] Here is a high-level description of the Benchmark Scenarios. Details of these scenarios can be found in Meadows et al. (1974), Meadows et al. (2004), and Cellier (2019).

Benchmark Scenario 1 (the "business-as-usual" (BAU), scenario) (Meadows et al., 2004, pp. 168-171)**)**. In Benchmark Scenario 1, human practices and policies continue without significant deviation from 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 1 shows population as a function of time in *World3* Benchmark Scenario 1. Figure 2 shows life expectancy as a function of time in that Scenario. Figure 3 shows food produced per capita as a function of time in that Scenario.

[4] 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 Scenario 9 with the sustainability policies of 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 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, those two scenarios were excluded from further consideration here.

[5] 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.

[6] Some *World3* predictions past Year 2100 likely lie well outside the calibration space of the simulator.

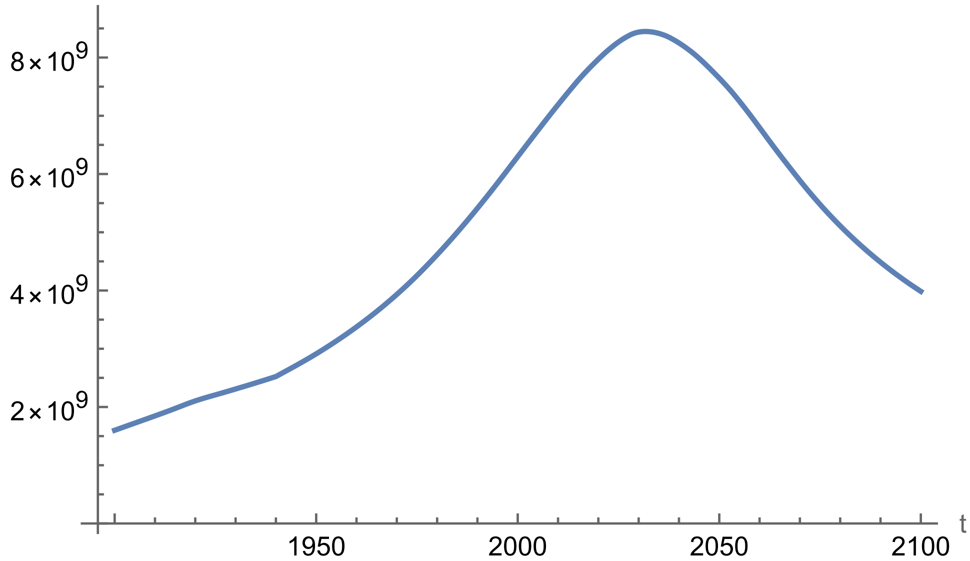

Figure 1. World population (number of persons) by time. *World3,* Benchmark Scenario 1 ("Business as Usual" (BAU)). Horizontal axis is calendar year. Note the population collapse beginning about Year 2030.

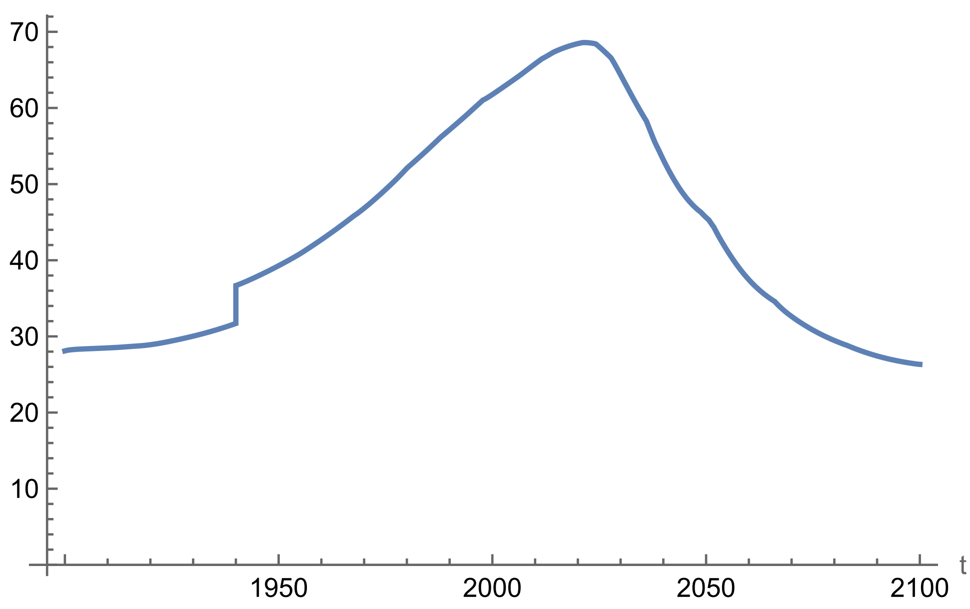

Figure 2. World average Life Expectancy (in years) by time. *World3,* Benchmark Scenario 1. Horizontal axis is calendar year. Note the drop in life expectancy beginning about Year 2025.

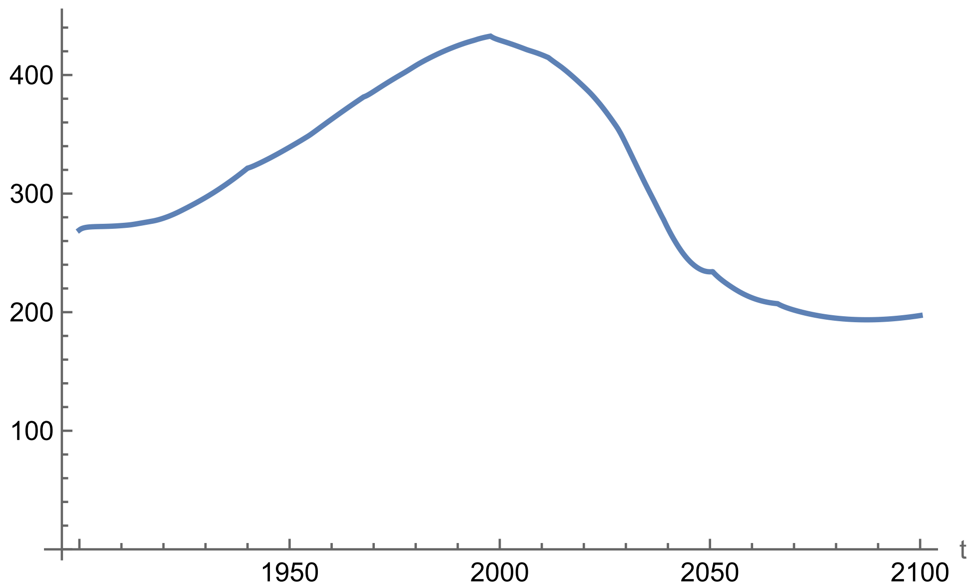

Figure 3. World food production (in vegetable-equivalent kilograms per person per year) by time. *World3,* Benchmark Scenario 1. Horizontal axis is calendar year. Note the drop in food production beginning about Year 2000.

Benchmark Scenario 2 (Meadows et al., 2004, pp. 172-174). In this scenario, the nonrenewable resources assumed in Benchmark Scenario 1 are doubled. Benchmark 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 Benchmark 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 et al., 2004, pp. 210-214). This scenario assumes the nonrenewable resource supply and extraction technologies assumed in Benchmark 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 et al., 2004, pp. 214-216). This scenario adds to the pollution control technology of Benchmark Scenario 3 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 et al., 2004, pp. 216-218). This scenario assumes more accessible nonrenewable resources, a better land-preservation technology than Benchmark 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 et al., 2004, pp. 218-220). This scenario assumes the world develops even more powerful pollution abatement and land protection than Benchmark 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 et al., 2004, pp. 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 Benchmark Scenario 2).

Benchmark Scenario 8 (Meadows et al., 2004, pp. 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.

Benchmark Scenario 9 (Meadows et al., 2004, 244-247). In this scenario, population and industrial output are limited as in Benchmark 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 4 shows population as a function of time in *World3* Benchmark Scenario 9. Figure 5 shows life expectancy as a function of time in Scenario 9. Figure 6 shows food produced per capita as a function of time in Benchmark Scenario 9.

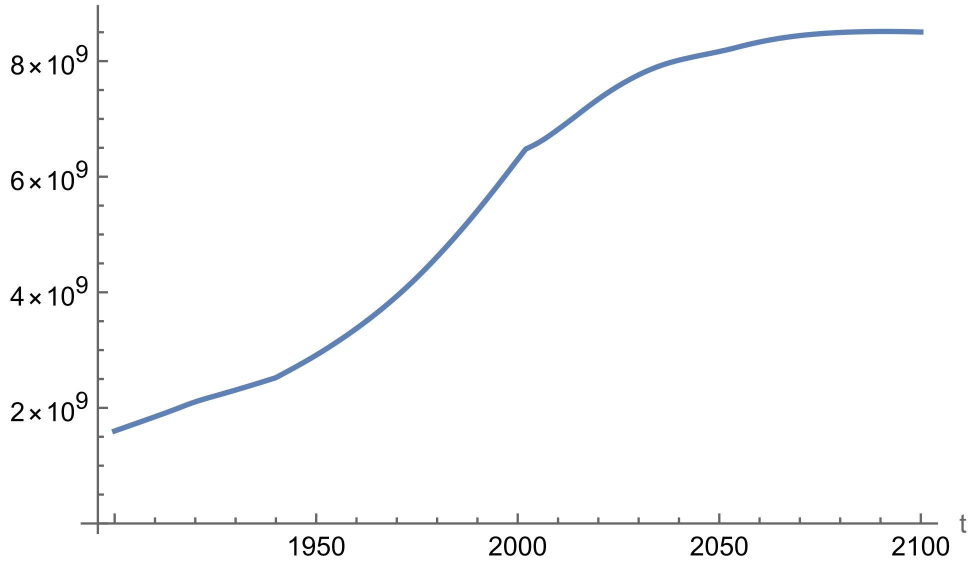

Figure 4. World population (number of persons) vs. time. *World3,* Benchmark Scenario 9. Horizontal axis is calendar year. Note the population is approximately constant starting about Year 2070. Compare with Figure 1.

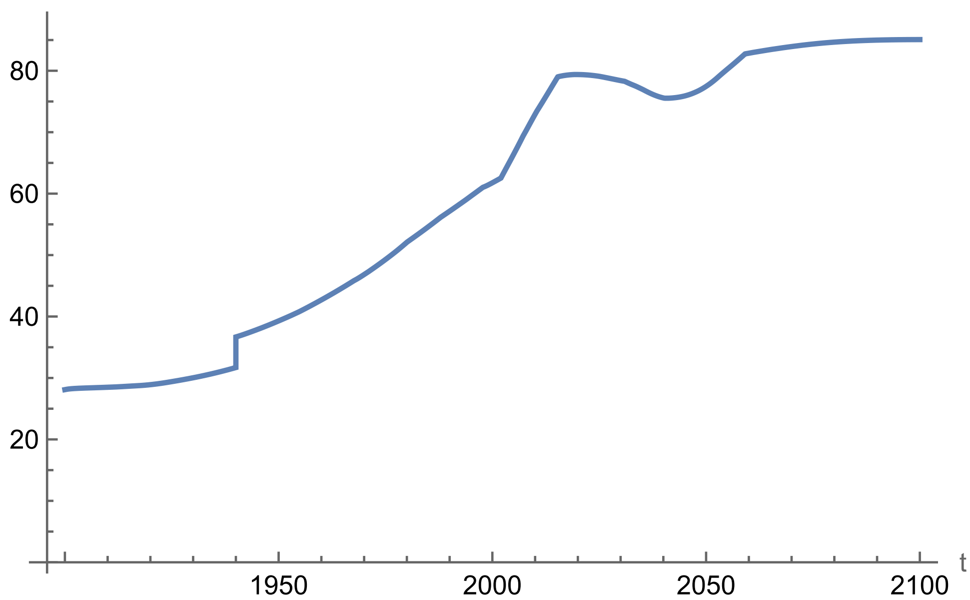

Figure 5. World average Life Expectancy (years) by time. *World3*, Benchmark Scenario 9. Horizontal axis is calendar year. Note that the life expectancy is constant starting about Year 2060. Compare with Figure 2.

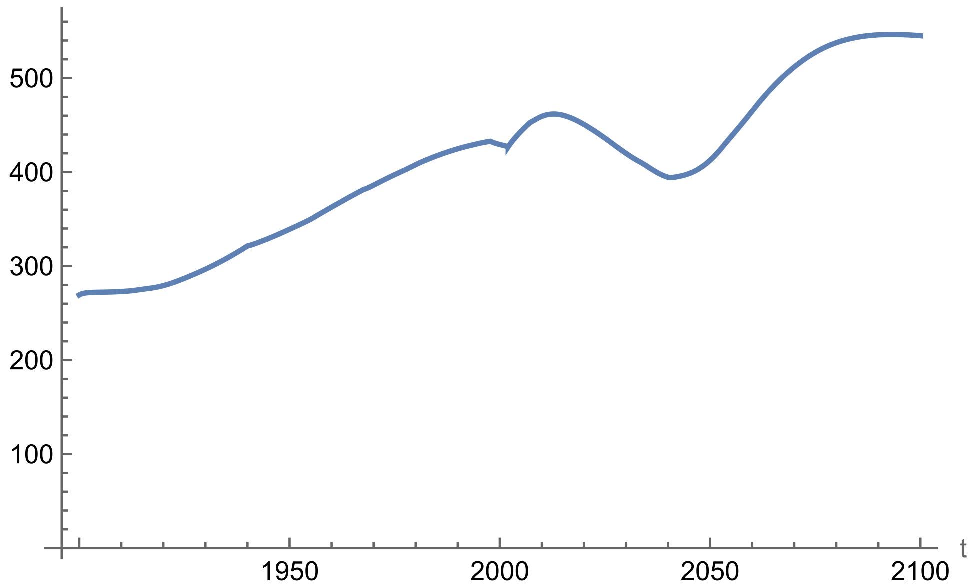

Figure 6. World food production (in vegetable-equivalent kilograms per person-year) by time. *World3*, Benchmark Scenario 9. Horizontal axis is calendar year. Note that food production is constant starting about Year 2080. Compare with Figure 3.

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 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. In the presence of adequate resources, population tends to increase exponentially but the resources required to sustain that population increase at best linearly. Over at least the last century, for example, 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*, increased only linearly. Of the Benchmark Scenarios, only Benchmark Scenario 9 avoids such a collapse.[7]

[7] 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 Benchmark

3.0 Method

The version (Cellier, 2019) of *World3* used in this study is Cellier (2008) hosted under the *System Modeler/Mathematica* ((Wolfram, 2019), (Wolfram, 2023)) framework. The configuration files for each of Benchmark Scenarios 1-9 are bundled with Cellier (2019). *Modelica* v3.2.2 and v3.2.3 provided the *Modelica* resources required by Cellier (2019).[8] Microsoft C++ Visual Studio provided the C++ resources required by Wolfram (2019) and Wolfram (2023). 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.

3.1 Selection of parameters to vary

Two criteria of adequacy must be satisfied in order to evaluate the response 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.

Note that when "response 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 response analysis is instead concerned with the question how, within *M*, *Y* varies with *X* (*X*').[9]\

A simulator can respond to variation in

a. Its inputs.
b. Its parameters.
c. The values of its variables.
d. Through variables or functions added to the simulator.

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. (1972) and Cellier (2019) are minor.

[8] If Cellier (2019) is executed interactively from *SystemModeler* (Wolfram, 2019), 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 *Modelica* v3.2.2.. If the software used in this study is executed under *Mathematica* (Wolfram 2022), *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.

[9] 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.

e. Subsets of (a)-(d).

There are tradeoffs, primarily involving simulator baselining and calibration issues, in any of these approaches. For this paper, approach (b) was selected. To implement approach (b) for the purposes of the present study, we must identify a parameter in *World3* that is related to the effects of climate change on wheat.

Global average temperature change is among the most immediate effects of climate change. The temperature trajectories implied by IPCC scenarios RCP4.5 (NOAA 2023a) and RCP8.5 (NOAA 2023b) were selected for this study.

Wheat production is sensitive to the temperature ranges spanned by RCP4.5 and RCP8.5. The optimum temperature over the entire growing season for more than 90% of the wheat produced today is about 17-23 °C (Porter and Gawith 1999, page 25). IPCC models RCP4.5 and RCP8.5 (van Vuuren 2011) imply that, by 2080, the average surface temperature during a large fraction of the wheat growing season will exceed 29 °C in the principal wheat-growing regions of the planet. At 29 °C during the growing season, at least 70% of today's level of world wheat production would be lost (Porter and Gawith 1999, Table 1, page 15, assuming normal distributions of the data in that Table).

World3 does not explicitly model temperature effects as such, but it does model (agricultural crop) land yield (LY), which is causally affected by temperature. *World3* contains a dimensionless parameter, however -- LYF1, called **p_land_yield_fact_1** in Cellier 2019 -- that by design (Meadows et al. 1974, p. 307) allows the user to define variation in LY caused by any user-designated cause that is consistent with the intended application semantics (see Turner 2011 for a discussion of this term) of the rest of *World3*. *World3* in effect multiplies LY by LFY1, as shown in Eq. 1. Eq. 1 is the only use of LFY1 in *World3* (Meadows et al 1974, p. 307; Cellier 2019):[10]

$$LY = LFY1 * LFERT * LYMC * LYMAP \qquad \text{Eq. 1}$$

where LY and LYF1 are as noted above and
LFERT is a land fertility multiplier
LYMC is a land-yield multiplier from capital (investment)
LYMAP is a land-yield multiplier from air pollution

Temperature as such is not modeled in *World3*, so we are free to use LFY1 as a proxy for the effects of temperature in *World3*. If LFY1 = 1.0, LFY1 has no effect on the value of LY.[11] By design, setting parameter LYF1 to less than 0.7 causes *World3* to exit on a *Modelica* ASSERT

[10] For the sake of succinctness, the time-step indices contained in the full form of LY in Meadows et al. 1974 are suppressed here.
[11] Benchmark Scenarios 1-9 set LFY1 to 1.0.

constraint.[12] Thus, in *World3* the permitted values of LFY1 lie in [0.7, 1.0]. Put another way, LFY1 can decrease LY by (100(1.0 – 1.0) = 0% to (100(1.0 – 0.7) =) 30%. The range of variation in LY induced by LYF1 lies entirely within the land-yield-loss effects of the temperature trajectories of scenarios RCP4.5 and RCP8.5. Thus, all else being the same, LFY1 can be used as a linear proxy[13] for 0% -30% of the loss of land-yield-loss (in this case, loss of wheat-production-loss) effects of the temperature trajectories of RCP4.5 and RCP8.5.

By convention, the standard reporting of the results of Benchmark Scenarios 1-9 documents the trajectories of the 11 World3 variables shown in Table 3:

Table 3. List of *World3* variables analyzed in this study. See Meadows et al. (1974) and Cellier (2019) for definitions of these variables.

***World3* variable**
Population
Food (Production)
Life Expectancy
Land Yield
Human Welfare Index
Human Ecological Footprint
Food Production Per Capita[14]
Industrial Output
Labor Utilization
Persistent Pollution
Non-renewable Natural Resources

Accordingly, for each of Benchmark Scenarios 1-9, the value of LFY1 was set to each of {0.7, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0}, and the effect of this variation, in Benchmark Scenarios 1-9, on the 11 *World3* variables shown in Table 3 was computed.

4.0 Results

The source code and results described in Section 2.0 were saved to a PDF file, available at Horner (2023).

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[12] It is not clear, based on Meadows et al. (1974) and Cellier (2019), why *World3* implements this specific ASSERT constraint.
[13] In general, the relationship between LY and *temperature* (see for example, Rosenzweig and Iglesias 1994) is not linear and in some regimes LY may not even be monotonic (Rudin 1964, Def. 3.13) in temperature.
[14] Food Production Per Capita is defined as F/POP, where POP is population.

Figures 1 – 6 (above) illustrate how *World3* system variables population, life expectancy, and food production vary in Benchmark Scenarios 1 and 9 when **p_land_yield_fact_1** is set to 1. Figures 7-12 (below) show how those same variables vary in Benchmark Scenarios 1 and 9 when **p_land_yield_fact_1** is set to 0.7. Horner (2023) shows how all variables listed in Table3 vary when **p_land_yield_fact_1** is set to each of the values in {0.7, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0}.

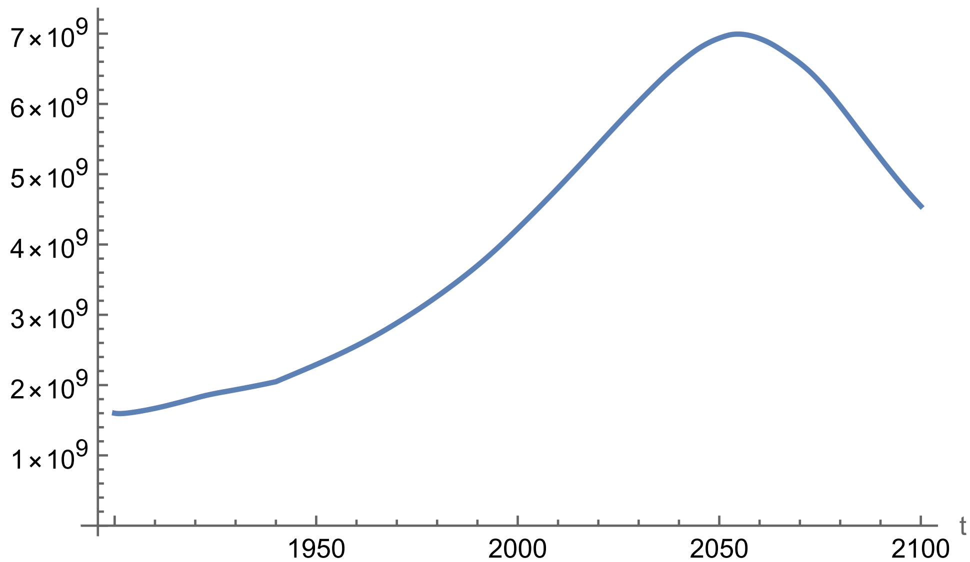

Figure 7. Population, people. Benchmark Scenario 1. p_land_yield_fact_1 = 0.7. Horizontal axis is calendar year. Note the population collapse starting at about Year 2050. The peak population in this Figure is about 7 billion. Compare with Figure 1, in which p_land_yield_fact_1 = 1.0, the peak population is about 8.4 billion.

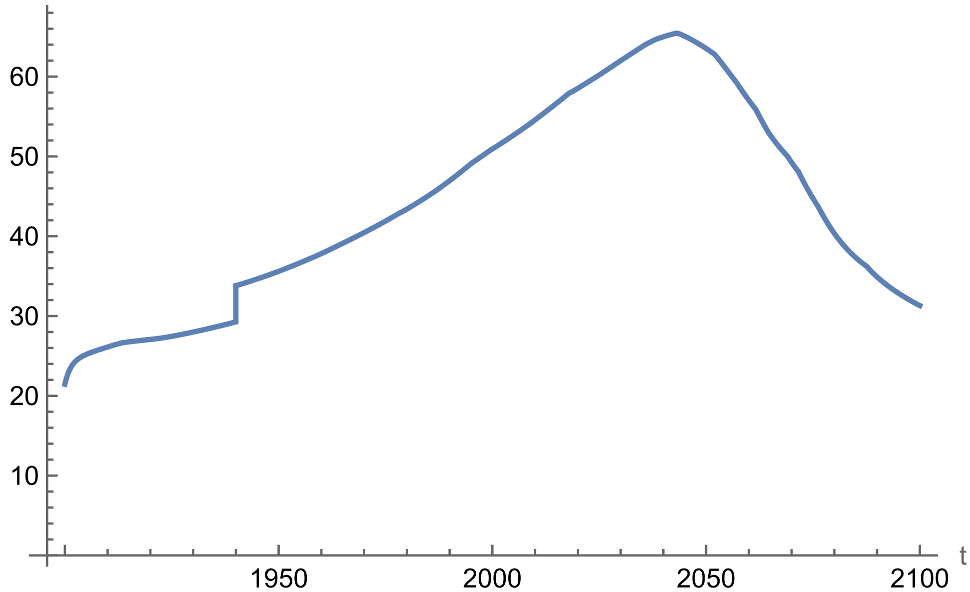

Figure 8. Life expectancy, years. Benchmark Scenario 1. p_land_yield_fact_1 = 0.7. Horizontal axis is calendar year. Peak life expectancy (65 years) occurs at about Year 2045. Compare with Figure 2, in which peak life expectancy occurs at about 75 years in Year 2025. Note the life expectancy drop starting at about Year 2050.

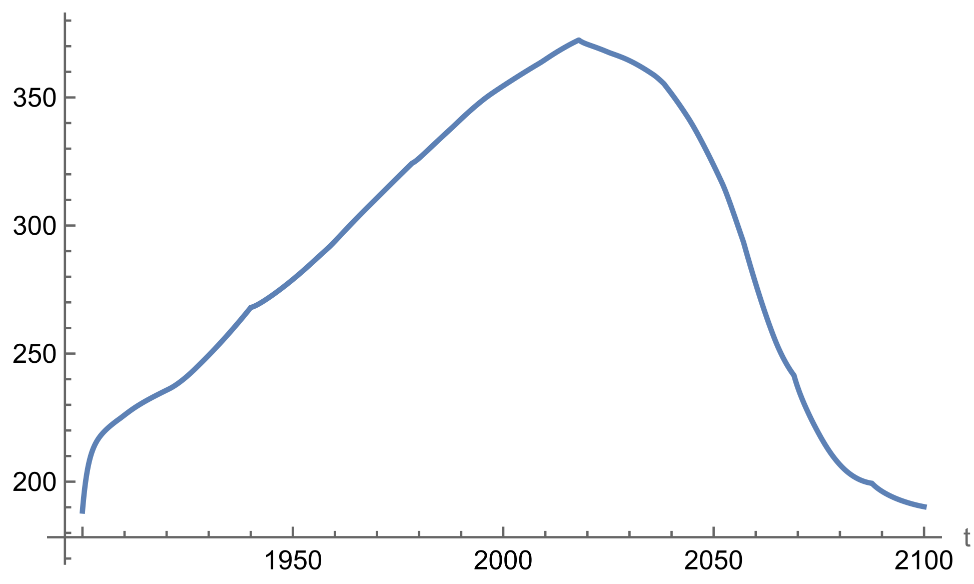

Figure 9. Food production, vegetable-equivalent kilograms per year per person. Benchmark Scenario 1. p_land_yield_fact_1 = 0.7. Peak production (about 380 vegetable-equivalent kilograms per year per person) occurs at about Year 2020. Horizontal axis is calendar year. Note the food production drop starting at about Year 2020.

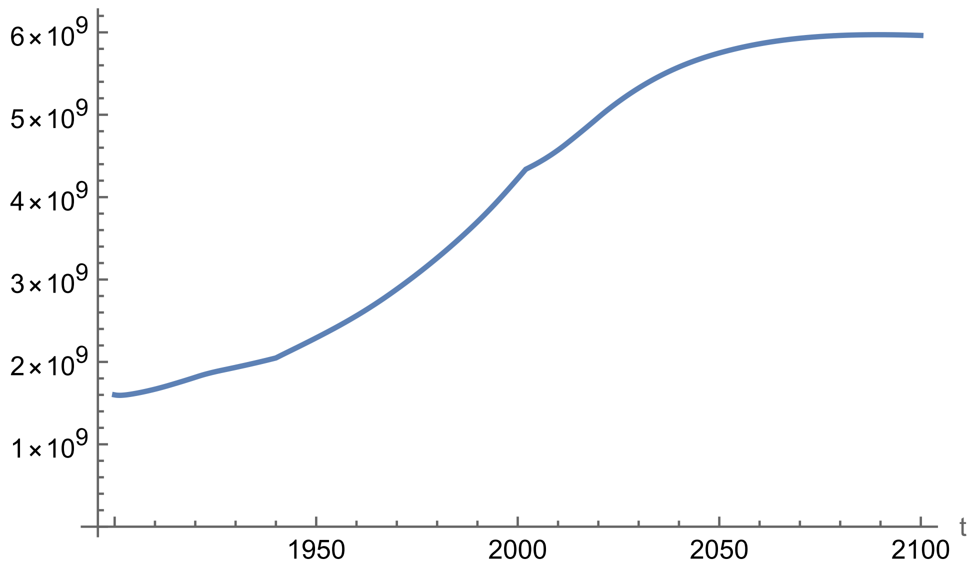

Figure 10. Population, people. Benchmark Scenario 9. p_land_yield_fact_1 = 0.7. Horizontal axis is calendar year. Note that population remains approximately constant after Year 2050. Compare with Figure 7.

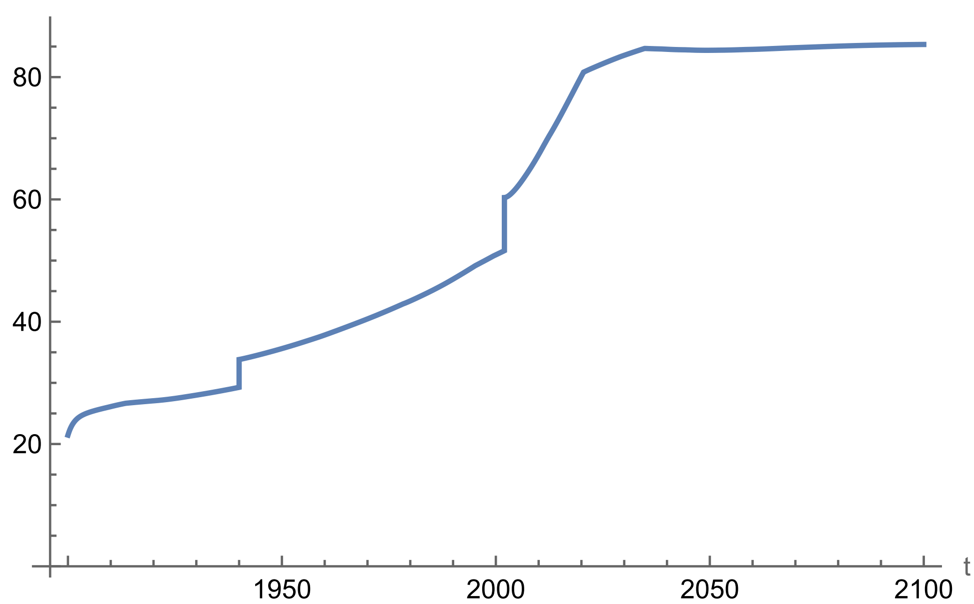

Figure 11. Life expectancy, years. Benchmark Scenario 9. p_land_yield_fact_1 = 0.7. Horizontal axis is calendar year. Note that life expectancy is approximately constant after Year 2020. Compare with Figure 8.

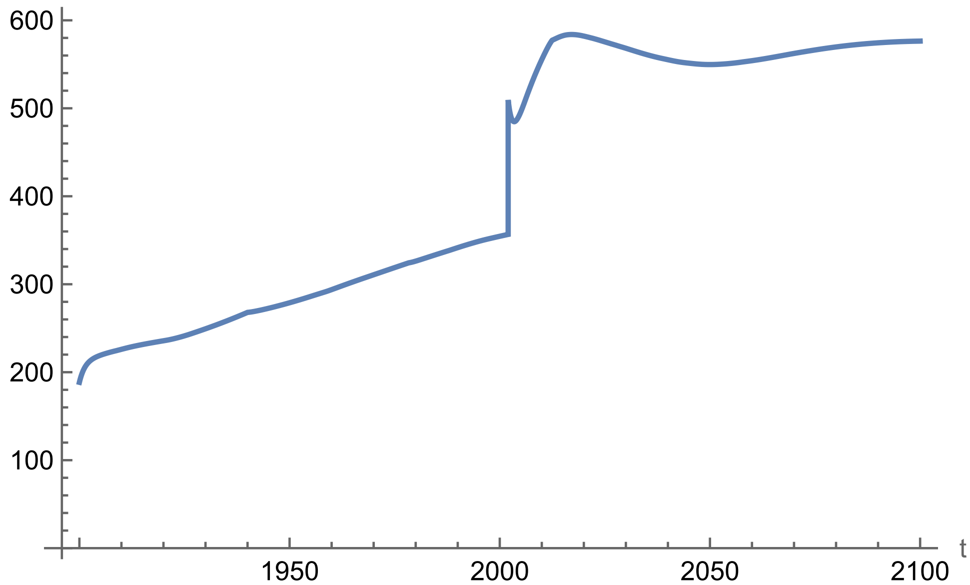

Figure 12. Food production, vegetable-equivalent kilograms per year per capita. Benchmark Scenario 9. p_land_yield_fact_1 = 0.7. Horizontal axis is calendar year. Note that food production is approximately constant after Year 2025. Compare with Figure 9.

The results shown in Figures 7-12, together with Horner (2023), show the response, *within World3*, of population-system variables in Table 3 to variation in LY caused by variation in the values of LY1 in {0.7, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0}. The resulting LY values are a subset of the land-yield-effects (for wheat) of the temperature profiles of RCP4.5 and RCP8.5. The results strongly suggest that *none* of the Benchmark Scenarios can mitigate all of the population-system effects of wheat-production loss due to IPCC scenarios RCP4.5 and RCP8.5. Of the lot, Benchmark Scenario 9 tempers those effects better, but only relatively so, than any of the other Benchmark Scenarios.

The total wall-clock time to execute all 63 scenarios documented in Horner (2023) was approximately 3 hours, corresponding to about 10^{14} machine-operations on the platform described in Section 2.0.

5.0 Discussion

The results in Section 4.0 motivate several observations.

1. Using *World3* to help probe the interaction of human population-system dynamics and wheat production is not a panacea: the effects of loss of wheat production on population-system

dynamics might lie outside what *World3* per se can plausibly represent.[15] It has been suggested, for example, that there are some wheat varieties that have a much better temperature tolerance than the varieties that currently dominate world production (see for example Potter and Gawith 1999, page 27). All we have to do, that suggestion says, is to switch the bulk of wheat production to these temperature-tolerant varieties, and the problem of wheat-production loss is solved. In such cases, using *World3* to help bound estimates of the interaction of loss of wheat production, and the remaining *World3* variables, 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*: broadly considered, it applies to *all* simulation regimes, and for that matter, all empirical predictive reasoning regimes that have not been, or for various pragmatic reasons (e.g., ethical, financial, technological) cannot be, tested.

In addition, although the proposal to switch to temperature-tolerant varieties is appealing, it glosses over at least two further difficulties. First, such switches require an inventory of seed wheat adequate to meet the need, and such an inventory would first have to be grown because it does not now exist. That program alone could easily take 10 years, if 1% of each year's wheat crop were saved for seed. Second, any alternative to the dominant varieties of wheat would have to be tolerant of the temperature trajectory implied by RCP4.5 and RCP8.5 for the entire wheat growing season, not just the maximum temperature during that season (Porter and Gawith 1999, pages 27-29). At present, none of the dominant wheat varieties produced today could satisfy this requirement.

2. It has been argued by several *World3* critics that technological changes could render any "world-system" simulator, including *World3*, predictions moot. Furthermore, proponents of this family of arguments assert, *World3* does not address this issue. Increases in agricultural productivity, one variant of that argument goes, could solve a wheat 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. Such arguments, though plausible at face, are problematic for at least three reasons.

First, some variants of this kind of argument are intended to be implicit proxies for a more general argument that applies to any simulation, not just to *World3*. *Anything* that changes the assumptions of a given simulation or reasoning scenario could cause the predictions to diverge

[15] Cellier (2019) implements range-of-value controls on ~100 variables, mainly to ensure that the numerical integration functions in *World3* operate within acceptable error limits. Some of these range-of-value controls coincidentally happen to abort scenarios that have parameter values that lie outside regions for which *World3* has been calibrated.

from the state of the actual world. But this is just a condition of human knowledge in general, not a specific problem in *World3* or of simulation in general.

Second, it is not true that the *World3* Benchmark Scenarios do not consider technological change. Each of Benchmark Scenarios 2-9 hypothesizes technological changes (including increased food productivity) with respect to Benchmark Scenario 1 (BAU). Benchmark Scenario 9, moreover, outlines the scope of a set of technological changes that could prevent the population-collapse problem.

Third, some "technological change" arguments do not even specify *which* technological changes would render *World3*'s predictions moot. As a consequence, such formulations are not testable even in principle, raising the question of whether those formulations are even part of empirical science. (See Hempel (1965), pp. 3-4, and Quine (1961), esp. Section 6).

3. It is sometimes argued that population-system dynamics models such as *World3* dynamics are inherently high-dimensional, and as a consequence using them entrains intractable calibration problems. Though this concern is not to be taken lightly, the Central Limit Theorem (Chung, 2001, esp. Chap. 7) ensures that Monte Carlo estimates of dynamics (Liu, 2001) in such systems at least converge.[16] ("Convergence" in this sense is a necessary, but not a sufficient, condition for "convergence to 'real-world' scenarios".) Maximum entropy techniques ((Jaynes, (1988)), (Kapur and Kesavan, (1992)), (Cover and Thomas, (1991), esp. Chap. 12), (Newman, (2010), esp. Chap. 15)) could also be used to estimate expected values of *World3* metrics.

Not least, high-dimensionality is not specific to *World3,* to simulation, or even to many domains of predictive reasoning in empirical systems.

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7.0 References

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[16] We could, in particular, use *World3* as the ensemble-generator in a Monte Carlo simulation. A Monte Carlo approach of this kind would require at least tera-scale computing resources.

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