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A *World3* analysis of the sensitivity of population-system dynamics to variation in non-renewable resources

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Abstract

Human population dynamics are a complex function of population growth intrinsic, industrial output, food production, and resource use. Some resources are non-renewable. The complete loss of some non-renewable resources (e.g., safe drinking water) could have lethal effects on the world population. Short of such a catastrophe, how does the availability of non-renewable resources affect population dynamics, and conversely? To help answer to this question, I use a well-characterized population-system dynamics simulator, *World3*, to compute the sensitivity of approximately 200 *World3* population-system variables to +/- 30% variation in non-renewable resources, for nine de facto "benchmark" *World3* scenarios. These scenarios span regimes ranging from the practices and policies 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 suggest that only one of these scenarios can globally achieve and sustain population stability and food security for humans between 2025 and 2100.

Keywords: Population/Resource Dynamics; Non-Renewable Resources; *World3*

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1. Introduction

This paper reports the results of using a well-characterized population-system dynamics simulator, *World3*, to compute the sensitivity of approximately 200 *World3* population-system variables to +/- 30% variation in non-renewable resources, for nine de facto “benchmark” *World3* scenarios. The remainder of Section 1 is an introduction to systems dynamics. Section 2 provides an overview of *World3*. Section 3 discusses the method used in this study. Section 4 contains a high-level view of the results of the study. Horner (2023) contains the detailed results of the study.

1.1. An overview of system dynamics

Ordinary science (Kuhn, 1970, esp. Chap. II) emphasizes formulating and testing experimental hypotheses that are cast in terms of scientific theories that are widely accepted. Research in ordinary chemistry, for example, concerns the structure and interactions of electronic orbitals. That research does not attempt to characterize interactions that we would consider to be wholly within the scope of, say, mathematical population dynamics (see for example Turchin, 2003). Similarly, research in ordinary agronomy (see for example Porter and Gawith, 1999) concerns practical optimizations in animal husbandry and agricultural crop production; it is not, as such, concerned with world reserves of say, silver ore (Statista, 2023).

Ordinary science does not exhaust the scope of science. We are often faced with scientific questions that are highly cross-disciplinary, and, for a variety of practical reasons (e.g., financial, ethical, time-critical) cannot at present be answered by the methods of, or within the scope of theories of, ordinary science. What, for example, is the relationship among agricultural production, capital investment, population size, and world reserves of non-renewable resources? What is the maximum human population that Earth can sustain? Answering to the best of our ability, questions of this kind require computer simulations of topics that do not fit entirely within the scope of currently accepted scientific theories. How, in such cases, should we proceed?

Forrester (1961) dubbed queries like these “systems dynamics” problems. This label encodes two important features of a large class of scientific problems that cannot be subsumed (at least currently) under ordinary science. First, “systems” are such by virtue the fact that their behavior is not reducible to a “sum of parts” explanatory rubric (see for example Kim, 2006). Second, many systems problems have inherently dynamic (i.e., time-varying) characteristics. Solving systems dynamics problems typically requires making models that are not as such subtheories of widely accepted scientific theories (although they may borrow terminology and principles from those theories). Often such models contain causal feedback loops that nonlinearly affect the values of at least some system variables.

Making and using system dynamics models involves several steps, in order (see Figure 1). Note that the scope of Figure 1 is not restricted to any particular application domain in science. It is a general-purpose methodology (Richmond, 2013). Systems dynamics analyses have proven to be a versatile and effective tool, finding applications across a diverse array of fields. These include business, where Sterman (2000) demonstrated their utility in organizational and market dynamics, mechanical engineering, with Davies and Schmitz (2015) applying them to understand and optimize mechanical systems, and electrical engineering, where Ebert et al. (2017) leveraged these analyses for enhancing electrical systems' efficiency and reliability. Additionally, health management has also benefitted from systems dynamics, as evidenced by Thompson and Tebbens (2009), who employed these methodologies for improving healthcare delivery and policy.

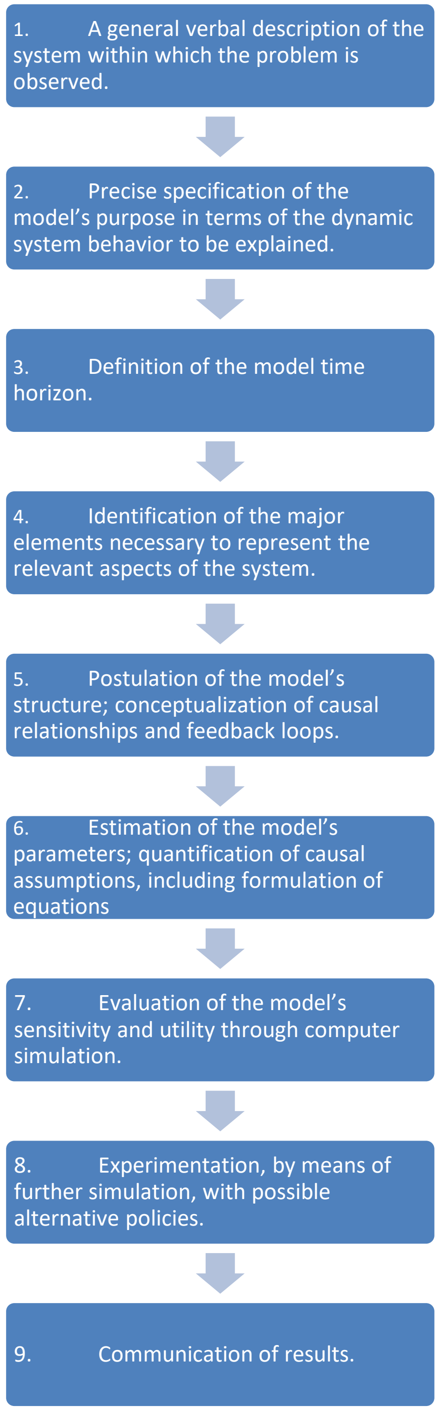

Figure 1. The steps in systems dynamics modeling (From Meadows et al. 1974, p. 5).

2. An overview of *World3*

The *World3* simulator (Meadows et al., 1974; Cellier, 2019; Wolfram, 2019; Wolfram, 2023) is a system dynamics simulator. It models, at a high level, the dynamical interaction of world population, pollution, agriculture, capital, and non-renewable resources. A dataflow diagram (DeMarco, 1978) of *World3* is shown in Figure 2.

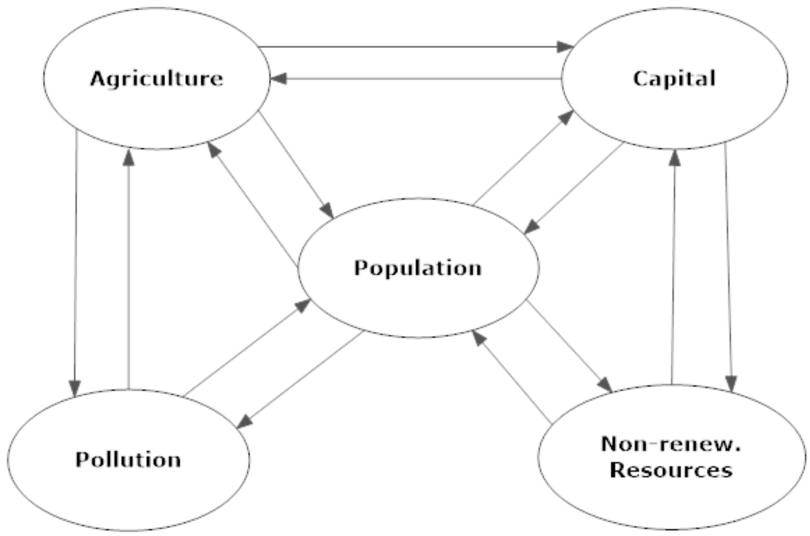

Figure 2. High-level dataflow diagram of *World3*. Arrows represent flow of data, tail to head, between data transforms (represented by ellipses). In the jargon of *World3*, the entities symbolized by ellipses are called Sectors. In total, *World3* contains about 300 system variables, about 300 equations, and about 100 parameters. Note that there are several feedback loops in Figure 1. For example, output from the Agricultural Sector causally affects Population, and conversely. Similarly, the Population Sector causally affects Pollution, and conversely. Non-renew. Resources = 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 2.1 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 2.1) 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 population (billions, from BAU Scenario)	UN estimate of world population (billions)	Percent difference between *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 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 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	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 somewhat more pessimistic than UN estimates for 2010 and 2020.

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* can be found in Meadows et al., 1974. The detailed physical design (in the sense of Boehm, 1981, Section 5.4; Boehm et al., 2000, pp. 312-313) of *World3* can be found 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).

2.1. The *World3* benchmark scenarios

Meadows et al. (2004) and Cellier (2019) describe, at a high level, nine de facto "benchmark" *World3* "benchmark" 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 Scenarios "the *World3* Benchmark Scenarios" or "the Benchmark Scenarios". Collectively, the Benchmark Scenarios provide a de facto baseline for analyzing the sensitivity of *World3* predictions to variations in *World3* parameters. By default, the duration of each Benchmark Scenario spans simulated calendar years 1900 - 2100. Here is a high-level description of 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. Branderhorst (2020) argues that among the Benchmark. Scenarios, the BAU Scenario most closely reflects the world system as of 2020.

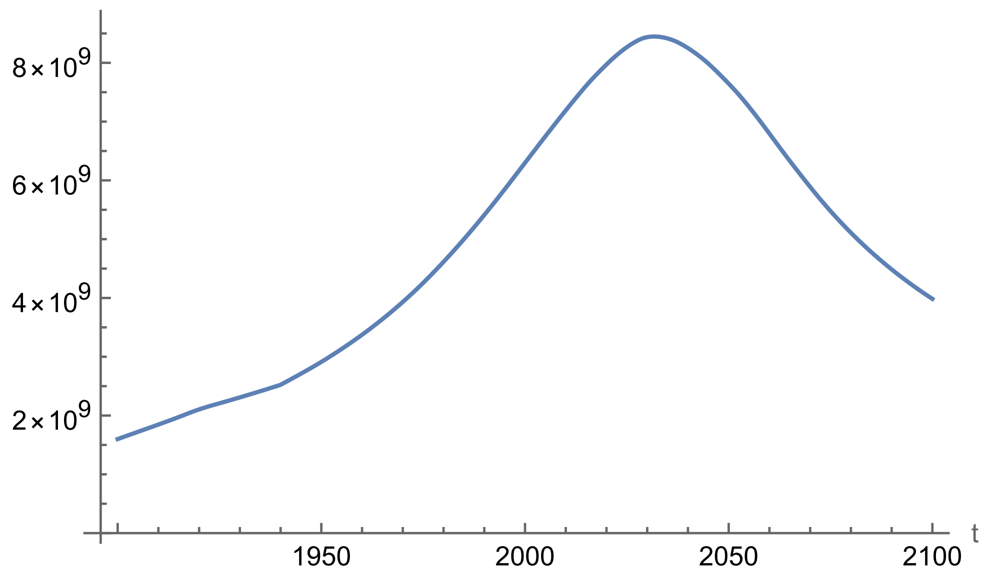

Figure 3. World population (number of persons) by time (Year). *World3*, Benchmark Scenario 1 (“Business as Usual”). Note the population “collapse” beginning about 2040.

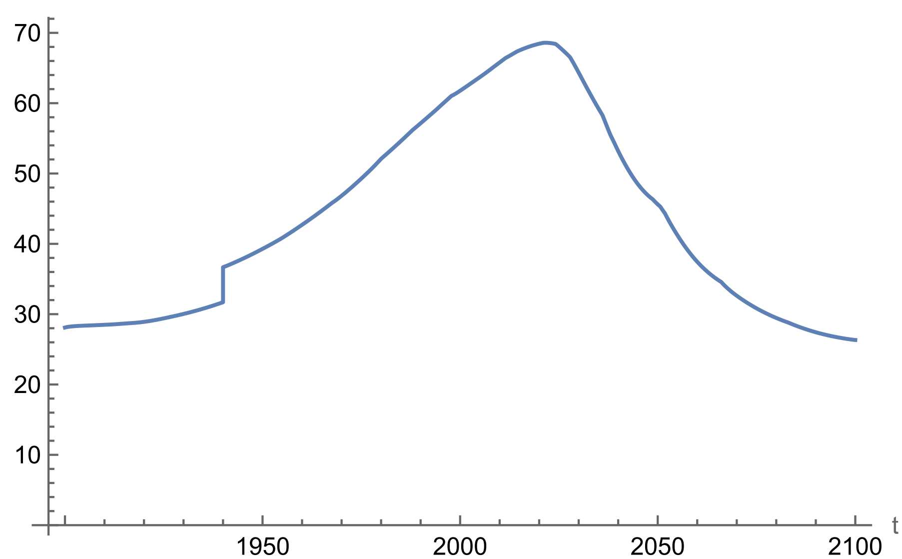

Figure 4. World average Life Expectancy (in years) by time (Year). *World3*, Benchmark Scenario 1. Note the sharp decline in average Life Expectancy beginning about 2030.

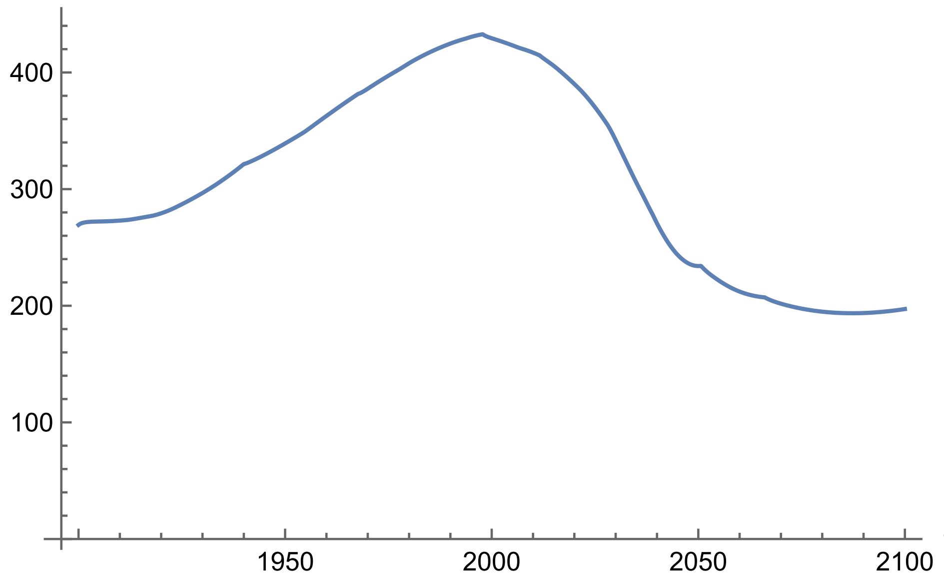

Figure 5. World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al., 1974), p. 64 for a definition of this term) by time (Year). *World3*, Benchmark Scenario 1. Note the sharp decline in per capita annual food production beginning about 2020.

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, pp. 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.

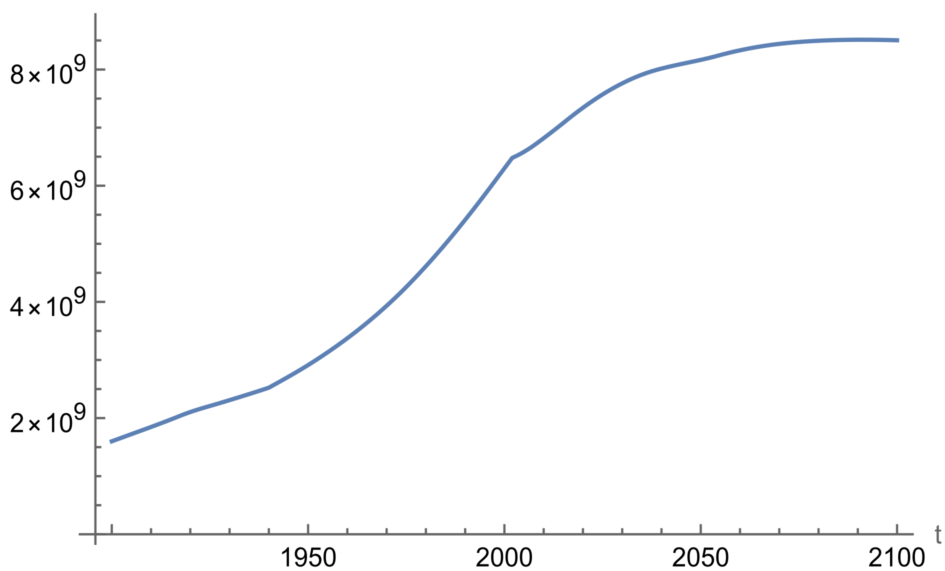

Figure 6. World population (number of persons) vs. time (Year). *World3*, Benchmark Scenario 9. Note that world population in this scenario is relatively constant starting about 2040.

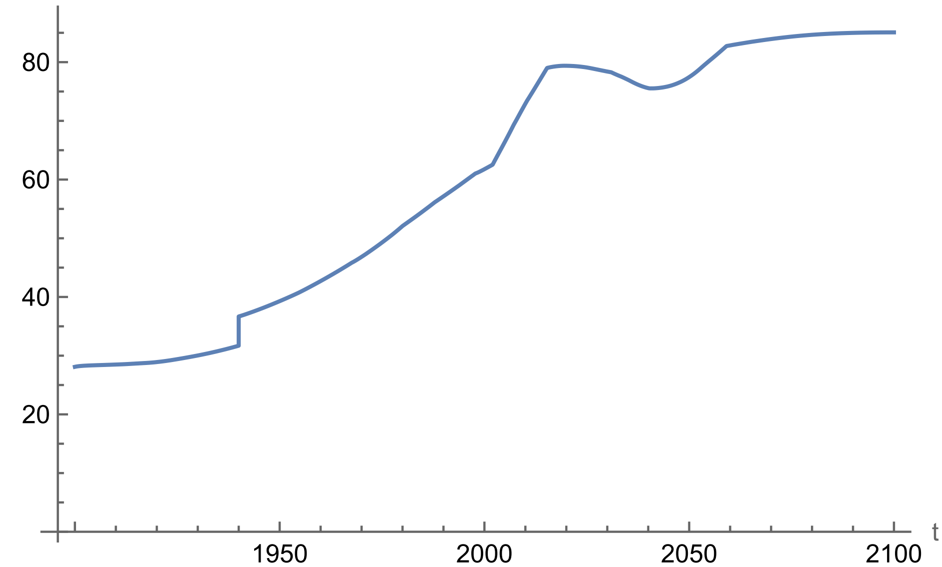

Figure 7. World average Life Expectancy (years) by time (Year). *World3*, Benchmark Scenario 9. Note that average Life Expectancy is relatively constant starting about 2060.

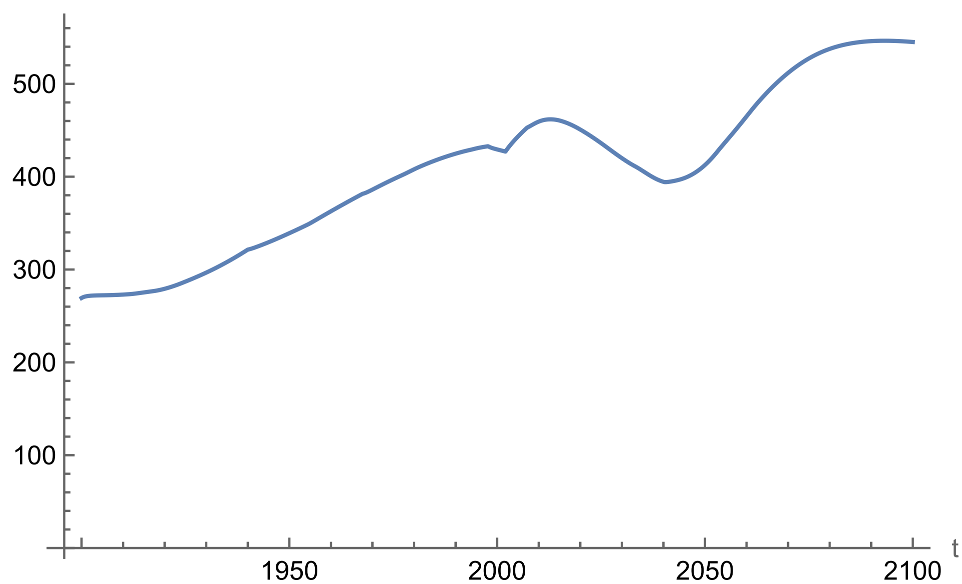

Figure 8. World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al., 1974), p. 64 for a definition), by time. *World3*, Benchmark Scenario 9. Note that per capita annual food production is relatively constant starting about 2080.

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 3). 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.

Of the *World3* simulation Sectors (population, pollution, agriculture, capital, and non-renewable resources) estimating (the initial value of) non-renewable resources is arguably the most difficult (see for example Meadows et al., 1974, Chap. 5). For the purpose of this study, I define a non-renewable resource (with respect to the duration of a scenario) to be a required resource whose replacement time is at least an order of magnitude larger than the duration of that scenario. In the present study, non-renewable resources include fossil fuels and non-recyclable metals (see Meadows et al. 1974, pp. 372-373 for a nominal list of these resources). The initial-value-normalized consumption rates of these resources vary widely and can be sensitive to changing technology regimes. All these issues, one way or another, raise the question of how sensitive *World3* scenarios are to the initial value of non-renewable resources.

3. Method

Cellier (2019) was used in this study, hosted under the *System Modeler* (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). Microsoft C++ Visual Studio provided the C++ resources required by Wolfram (2019) and Wolfram (2022). 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

This paper is primarily concerned with the application of Step 7 (sensitivity studies) of Figure 1 to *World3*'s Non-Renewable Resources. Sensitivity studies are essential in systems dynamics regimes for three reasons. First, they help to identify features of a model that are least likely to be accurate under uncertainty in model calibrations. Second, even where uncertainty is not an issue, sensitivity studies can help to identify dynamical regimes that are inherently unstable. And third, sensitivity studies can help to identify what level of detail in the simulator of interest is meaningful (not all details are relevant or tractable, so we must choose).

For the purposes of this paper, I define *Y to be sensitive to X* if the variation in the value of Y is greater than linear in the value of X. Put another way, Y is sensitive to X if Y is *superlinear* in X. For example, suppose Y is per capita food consumption and X is total population size. Suppose for example that doubling population size

(X) resulted in quadrupling the per capita food price (Y). Then by the definition of "sensitive" above, per capita food price would be sensitive to total population size.

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.

Note that 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*').

In addition to conforming to the steps and criteria in Figure 1, and to A1 and A2, I restricted the sensitivity analysis in this study to sensitivity with respect to the values of the *parameters* of the (in this case, *World3*) simulator satisfying Step 7 of Figure 1. This restriction helps to ensure that the basis for comparisons is well defined. (Sensitivity analyses that allow the identity of the members of the set of the system variables of a simulator to vary, in contrast, raise all manner of questions about comparability, identity, and tractability.) Given this constraint, we must find a *World3* parameter related to non-renewable resources, variation in whose values yields useful sensitivity information. (There is no guarantee that a given simulator will have such a parameter).

World3 contains a parameter, **nr_resources_init**, that estimates the quantity, at simulation-start, of non-renewable resources considered as an aggregate (see Meadows et al, 1974, Chap. 5). Benchmark Scenario 1 assumes that **nr_resources_init** has a value of 1 x 1012 (resource units), but Benchmark Scenarios 2-9 assume that **nr_resources_init** has a value of 2 x 1012 (resource units). Accordingly, a further scenario, here called Scenario 10, which is identical to Benchmark Scenario 9 except that **nr_resources_init** is given a value 1 x 10 (resource units), was added to the set of Benchmark Scenarios evaluated in the present study.

Eq. 1 shows the role that **nr_resources_init** plays in *World3*. Very simply, **nr_resources_init** just initializes non-renewable resources. **nr_resources_init** plays no further role in *World3*:

$$NR = NRI \qquad \text{(Eq. 1)}$$

where, NR is non-renewable resources, and NRI is nr_resources_init.

For each Benchmark Scenario, the value of **nr_resources_init** was varied by ±30%, and the effect of this variation on ~200 *World3* variables was analyzed. *The System Modeler/Mathematica* (Wolfram, 2019; (Wolfram, 2023) functions **SystemModelSimulateSensitivity** and **SystemModelPlot** were used to compute the sensitivity of the *World3* variables reported in this study. See Horner (2023) for further details.

4. Results

The sensitivity source code and results described in Section 3 were saved to a PDF file, available at Horner (2023). The collective wall-clock time for these calculations on the platform described in Section 2 was approximately 3 hours.

Figures 9-17 illustrate the sensitivity of three *World3* variables, including '**Food_Production1.Agr_Inp.Integrator1.y**', '**Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y**', and '**Population_Dynamics1.Pop_0_14.Integrator1.y**' in Benchmark Scenarios 1 and 9, and Scenario 10, to variation in **nr_resources_init**. In these Figures, the green curve corresponds to a +30% increase in the default value of **nr_resources_init**. The blue curve corresponds to the default value of nr_resources_init. The orange curve corresponds to a 30% decrease in the nominal value of **nr_resources_init**.

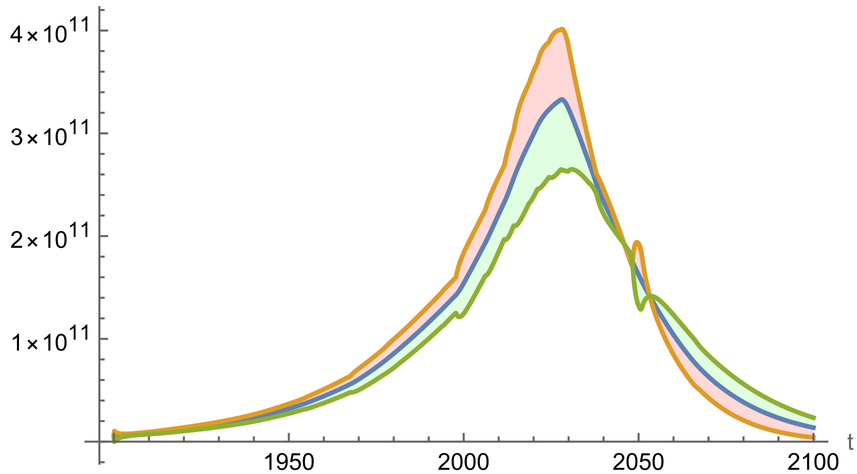

Figure 9. Sensitivity of **Food_Production1.Agr_Inp.Integrator1.y** to **nr_resources_init**. Benchmark Scenario 1. In this scenario, even at peak (about 2030), food production scales approximately linearly with the variation percentage variation about the nominal value.

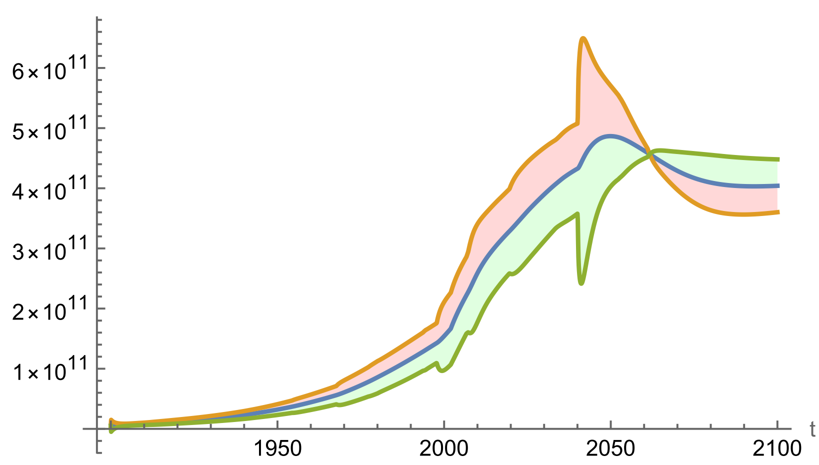

Figure 10. Sensitivity of **Food_Production1.Agr_Inp.Integrator1.y** to **nr_resources_init**. Benchmark Scenario 9. Note the significant increase in sensitivity, 2040-2060.

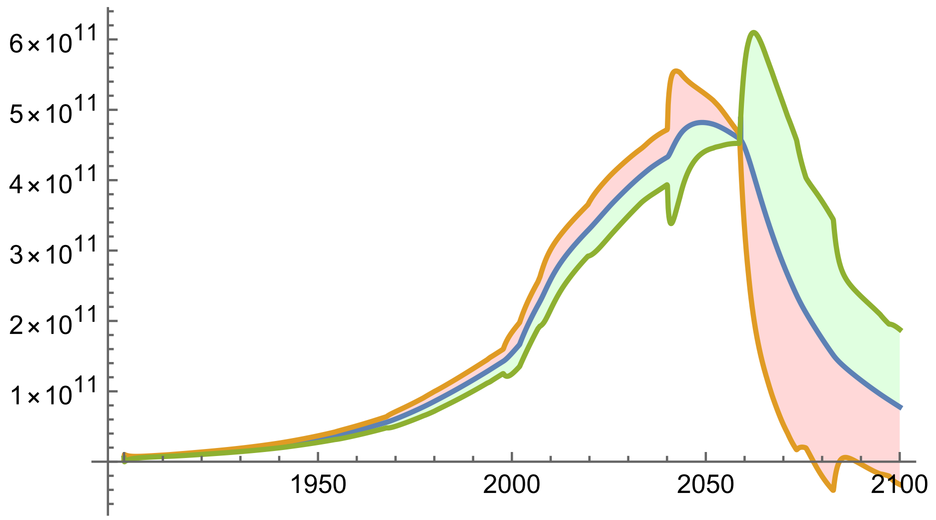

Figure 11. Sensitivity of **Food_Production1.Agr_Inp.Integrator1.y** to **nr_resources_init**. Scenario 10. Note the significant increase in sensitivity, 2080-2100.

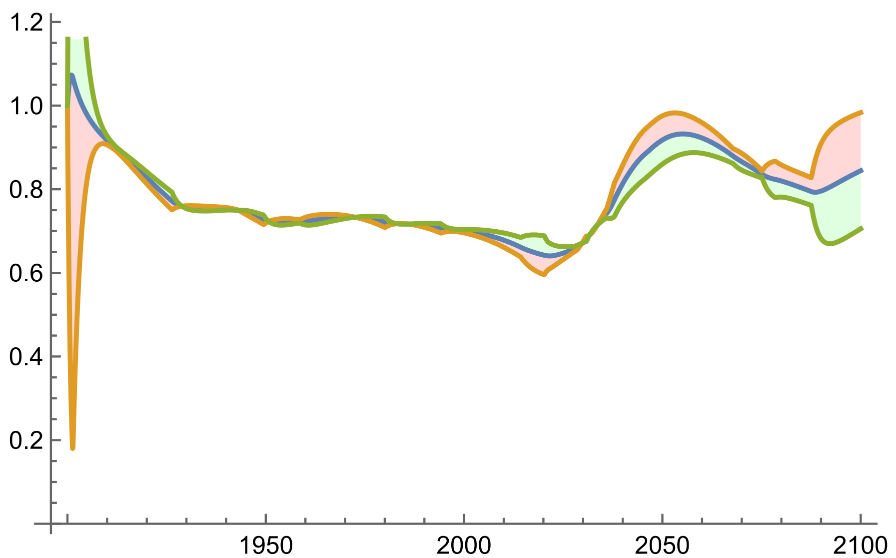

Figure 12. Sensitivity of Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y to **nr_resources_init**. Benchmark Scenario 1. Note the significant increase in sensitivity, 2080-2100, compared to 1920-1980.

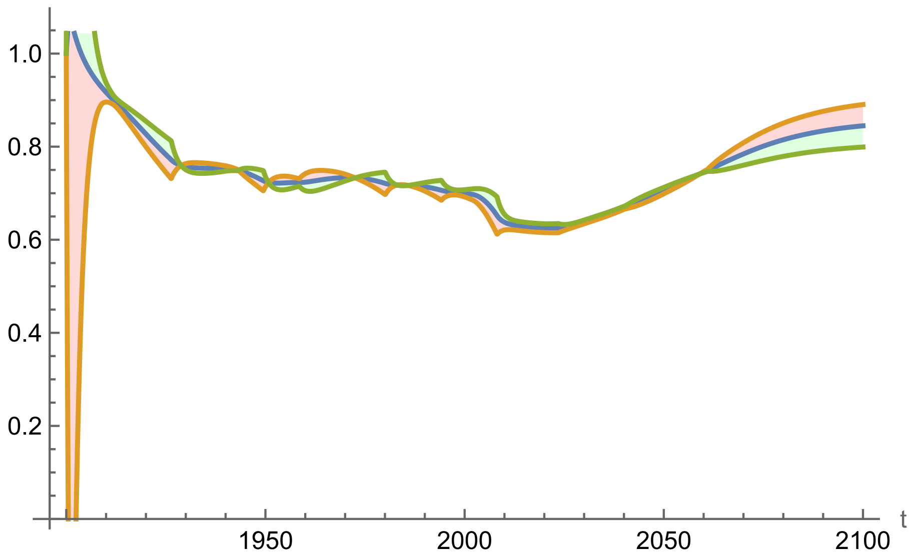

Figure 13. Sensitivity of **Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y** to **nr_resources_init**. Benchmark Scenario 9. The Figure shows that except for the period 1900-1910, Labor_Utilization is relatively insensitive to +/- 30% variation in nr_resources_init. (The nominal sensitivity of **Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y** to **nr_resources_init**, 1900-1910, in this Figure may be an integration-initialization artifact of the numerical integration algorithm used by SystemModelSimulateSensitivity).

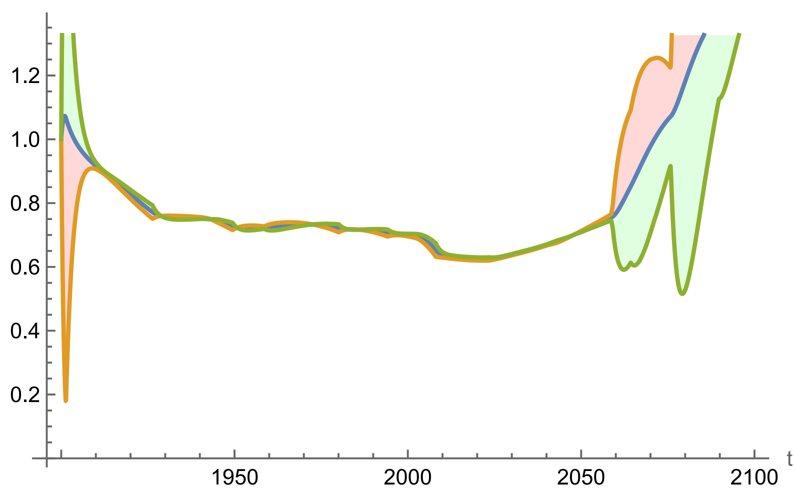

Figure 14. Sensitivity of **Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y** to **nr_resources_init**. Scenario 10. Note the significant increase in sensitivity beginning about 2060, compared to 1920-2060. (The nominal sensitivity of **Labor_Utilization1.labor_Util_Fr_Del.Integrator1.y** to **nr_resources_init**, 1900-1910, in this Figure may be an integration-initialization artifact of the numerical integration algorithm used by SystemModelSimulateSensitivity.)

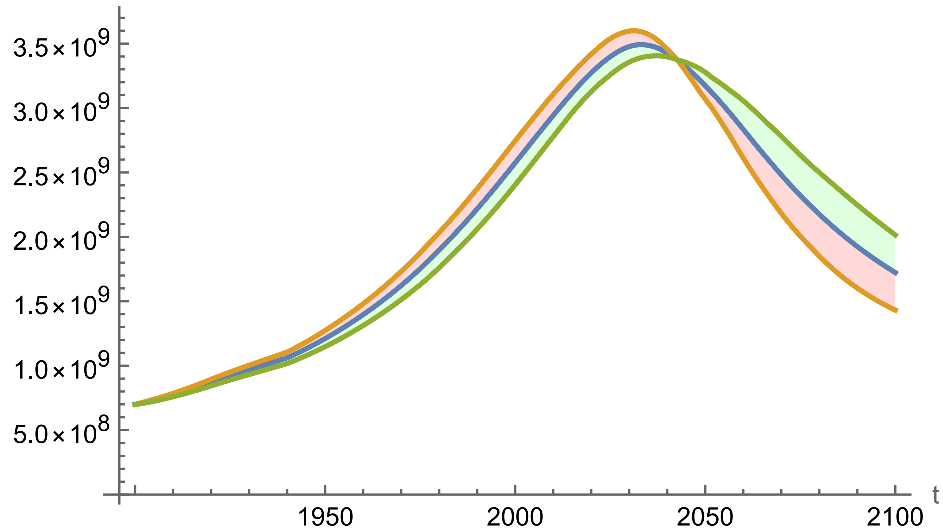

Figure 15. Sensitivity of **Population_Dynamics1.Pop_0_14. Sensitivity of Integrator1.y** to **nr_resources_init**. Benchmark Scenario 1. This segment of the population (ages 0-14 years) is relatively insensitive to variation in **nr_resources_init**, 1900-2100.

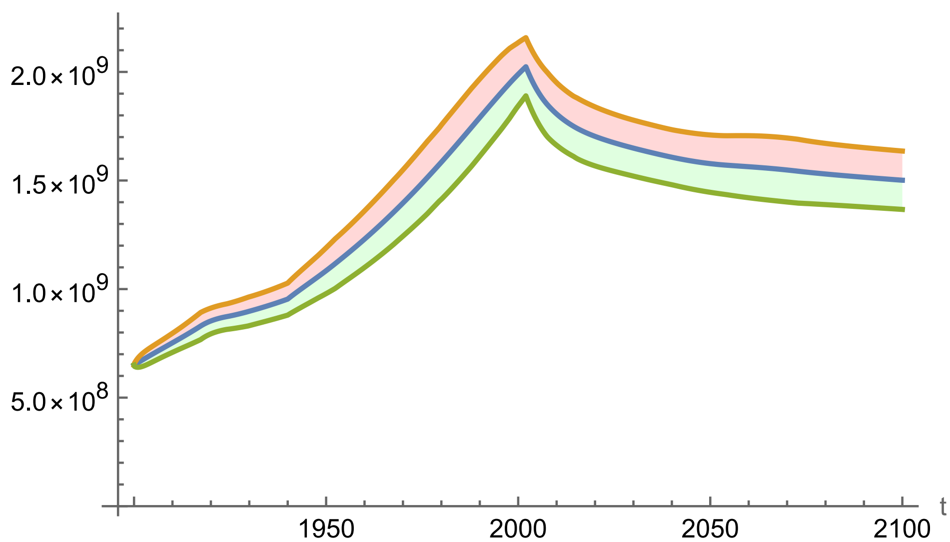

Figure 16. Sensitivity of **Population_Dynamics1.Pop_0_14**. Benchmark Scenario 9. This segment of the population (ages 0-14 years) is relatively insensitive to variation in **nr_resources_init**, 1900-2100.

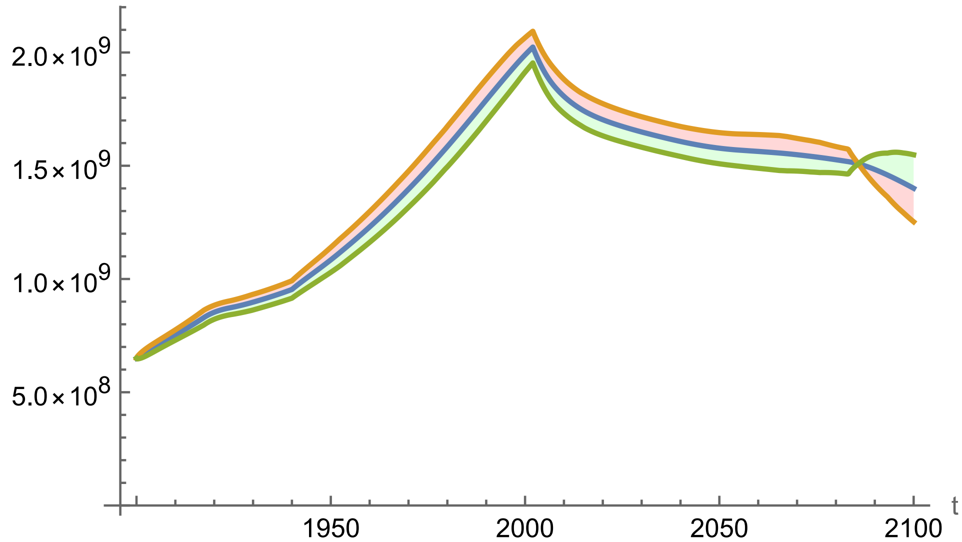

Figure 17. Sensitivity of **Population_Dynamics1.Pop_0_14.Integrator1.y** to **nr_resources_init**. Scenario 10. This segment of the population (ages 0-14 years) is relatively insensitive to variation in **nr_resources_init**, 1900-2100.

The results shown in Figures 9-17, together with Horner (2023), suggest that, among Benchmark Scenarios 1-9, and Scenario 10, only the population/resource-management policies and practices of World3's Benchmark Scenario 9 can globally achieve and thereafter sustain acceptable population stability and food security for humans between 2025 and 2100, given +/-30% variation in the initial value of non-renewable resources. As of 2023, world resource management and policy-making is approximately the same as that of Benchmark Scenario 1 (BAU). Little to no improvement in long-term population stability and food security with respect to the BAU Scenario has been realized since the early 1970s. (Note that in the BAU Scenario, the population and food supply collapses are predicted to start about 2030. Although in *World3*, population size and food supply are treated as global properties, this does not mean that those properties are distributed uniformly at all times. Current real-world trends in population growth and food supply show that population stability and food security problems are likely, at least initially, to be concentrated in sub-Saharan Africa and Southeast Asia (World-o-meter, 2023; UN Food and Agriculture Organization 2021).

5. Discussion

The results of the study motivate several observations.

1. Using *World3* to help probe the interaction of human population-system dynamics and non-renewable resources is not a panacea: the effects of non-renewable resources on population-system dynamics might lie outside what World3 per se can plausibly represent. If so, using World3 to help bound estimates of the interaction of non-renewable resources, 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: 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.

2. It has been argued by several *World3* critics that technological changes could render *World3*'s 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 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. Such arguments, though plausible at face, are problematic for at least three reasons.

First, this kind of argument is a particular case of 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 from the state of the actual world. This is just a condition of human knowledge in general.

Second, it is simply not true that the *World3* Benchmark Scenarios do not consider technological change. Each of Benchmark Scenarios 2-9, and Scenario 10, 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. ("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 to many domains of predictive reasoning in empirical systems.

4. It might be objected that aggregating, as *World3* does, all non-renewable resources can't be right. Some non-renewable resources are not as important as others, this objection might go, and the code needs to reflect such differences.

Although this objection would be fatal in some contexts, it is technically not so in the context of this study. This study is concerned with what can be expressed *within the resources of World3* as is, not about whether *World3* models the real world in all particulars as such.

Such a counter is not likely to satisfy anyone who wants to use world dynamics methods to inform policy and practice. The developers of *World3* were clearly attuned to this concern and set the value of **nr_resources_init in** the BAU Scenario to reflect the known reserves and consumption rate of those resources as of 1974. The effect of this choice, as executing the BAU Scenario shows, is not the cause of the population collapse in the BAU Scenario. (The population collapse in the BAU Scenario is primarily attributable to population overrunning food supply).

6. Future work

1. The method described above can be applied to other sustainability topics. For example, it is possible to use variation in the *World3* parameter, **p_land_yield_fact_1**, as a proxy for the loss of cereal grain production in Intergovernmental Panel on Climate Change (IPCC) scenarios RCP4.5 and RCP8.5 (van Duuren et al., 2011). The calculations for that study were completed in November 2023.
2. In principle we could add to *World3* new code that deals with specific non-renewable resources separately. For example, if, in order to help mitigate climate change, the industrialized world was to convert to all-electric vehicles, there would likely be a sharp increase in the per capita utilization of copper, cobalt, nickel, and lithium. New code would have to be added to *World3* to reflect those resource-usage dynamics.

There is no free lunch in extending a simulator like *World3* to represent phenomena it does not already do so. Any modification to World3 that extends its current calibration space would require re-calibration of the simulator. That calibration effort can hardly be overestimated. In general, the calibration of any simulator requires a large investment of testing labor, even supposing the task is tractable. (See Symons and Horner, 2014) and Symons and Horner (2020) for a discussion of issues concerning the intractability of exhaustively verifying even software systems much smaller than World3.) This kind of tradeoff is not specific to *World3*: it arises in all software-intensive studies.

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