International Journal of Development and Sustainability
ISSN: 2186-8662 – www.isdsnet.com/ijds
Volume 14 Number 2 (2025): Pages 150-165
https://doi.org/10.63212/IJDS24102001

A *World3* analysis of population-resource dynamics under climate-change-driven loss of wheat production

Jack K. Horner *

Independent Researcher, Lawrence, Kansas, USA

Abstract

IPCC climate models that predict a 5 °C or greater increase in global temperature (above the pre-industrial average) 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-resource dynamics simulator, *World3*, to compute the *World3* response of 12 *World3* population-resource variables to a 0% - 100% loss of wheat production, 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 strongly suggest that none of the Benchmark Scenarios can overcome all of the population-resource effects of wheat-production loss due to the temperature trajectories of IPCC scenario RCP4.5. Overcoming these effects will require that, over the next three to four decades, we achieve a 50% reduction in current greenhouse gas production rates and/or a wholesale replacement of the current dominant strains of wheat with significantly more heat-tolerant varieties.

Keywords: Population/Resource Dynamics; Climate Change; Wheat Production; IPCC Climate Models; *World3*

Cite this article as: Horner, J.K. (2025), "A *World3* analysis of population-resource dynamics under climate-change-driven loss of wheat production", *International Journal of Development and Sustainability*, Vol. 14 No. 2, pp. 150-165.

* Corresponding author. *E-mail address:* jhorner@cybermesa.com

1. Introduction

This paper describes a *World3*-based analysis (Meadows et al., 1974; Cellier, 2019; Nebel et al., 2023) of the response of population-resource dynamics to climate-change-driven loss of wheat production. Section 2 of the present paper provides an overview of *World3* and sets the context for the experiments reported in Sections 3 and 4.

2. Overview of *World3*

The *World3* simulator (Meadows et al., 1974; Cellier, 2008; Cellier, 2019; Wolfram, 2019; Nebel et al., 2023) is a system of approximately 330 equations and 330 variables that models, at a high level, the dynamical interaction of 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* (especially *World3's* Benchmark Scenario 1; see Section 2.1 of this paper) show that *World3* has predicted the trajectories of the system variables listed in Table 3 (see Section 3.3, below), including global population and food production well for Years 1900 - 2020. For example, 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 2.1) with the UN estimates (United Nations, 2019). Population is rounded to two significant figures; percent difference is computed as [(World3_prediction – UN_estimate) / UN_estimate] and 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.

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.

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. Percent difference is computed as [(World3_prediction – UN_estimate) / UN_estimate].

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

2.1. The *World3* benchmark scenarios

Meadows et al. (2004), Cellier (2019), and Nebel et al. (2023) 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:

- 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. Following is a high-level description of Benchmark Scenarios 1 (the "BAU" scenario) and 9. Details of these, and of Benchmark Scenarios 2-8, can be found in Meadows et al. (1974), Meadows et al. (2004), Cellier (2019), and Nebel et al. (2023).

Benchmark Scenario 1 (the "business-as-usual" (BAU) scenario; Meadows et al., 2004, pp. 168-171): In Benchmark Scenario 1, the practices and policies of most of the 20th century continue without significant deviation. As a result, population and production increase until growth is arrested 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 defined as 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.

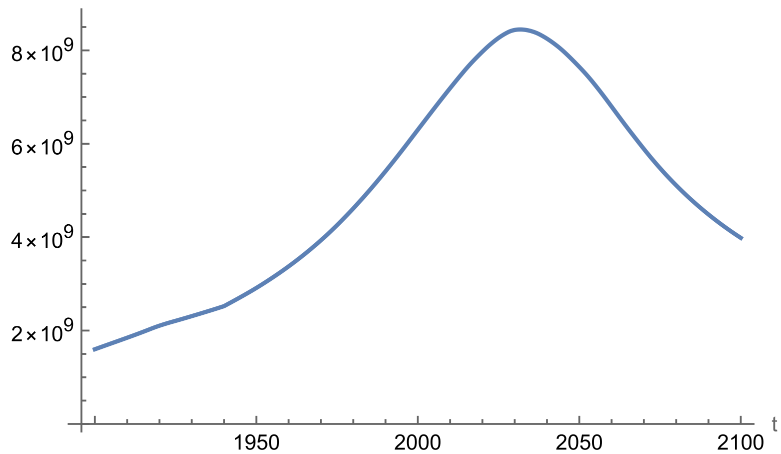

Figure 1. World population (number of persons) by time. *World3*, Benchmark Scenario 1 ("Business as Usual" (BAU)). Horizontal axis is calendar year. Note the population collapse beginning about Year 2030.

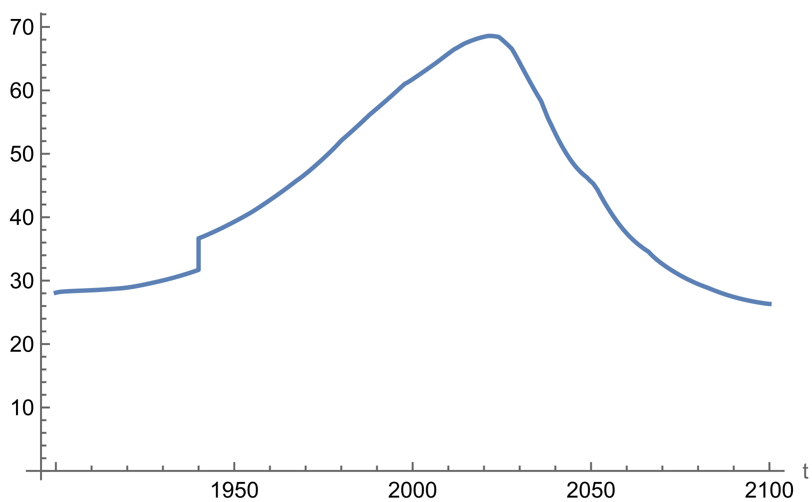

Figure 2. World average Life Expectancy (in years) by time. *World3*, Benchmark Scenario 1. Horizontal axis is calendar year. Note the drop in life expectancy beginning about Year 2025.

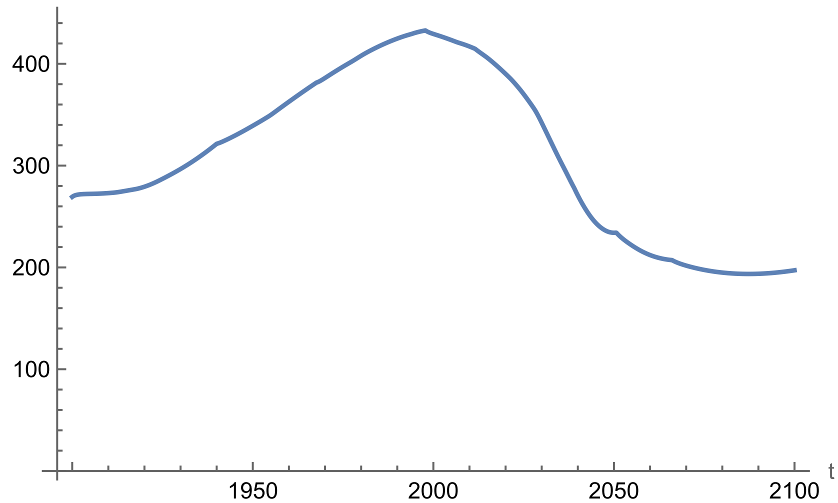

Figure 3. World food production (in vegetable-equivalent kilograms per person per year) by time. *World3*, Benchmark Scenario 1. Horizontal axis is calendar year. Note the drop in food production beginning about Year 2000.

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

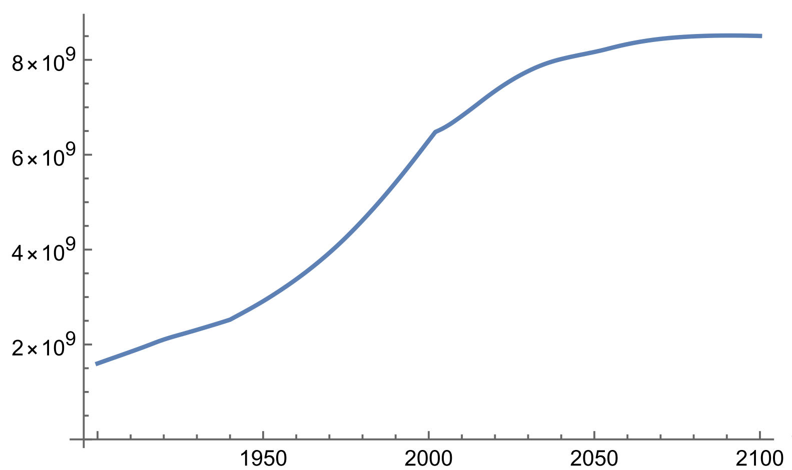

Figure 4. World population (number of persons) vs. time. *World3*, Benchmark Scenario 9. Horizontal axis is calendar year. Note the population is approximately constant starting about Year 2070. Compare with Figure 1 (from Benchmark Scenario 1).

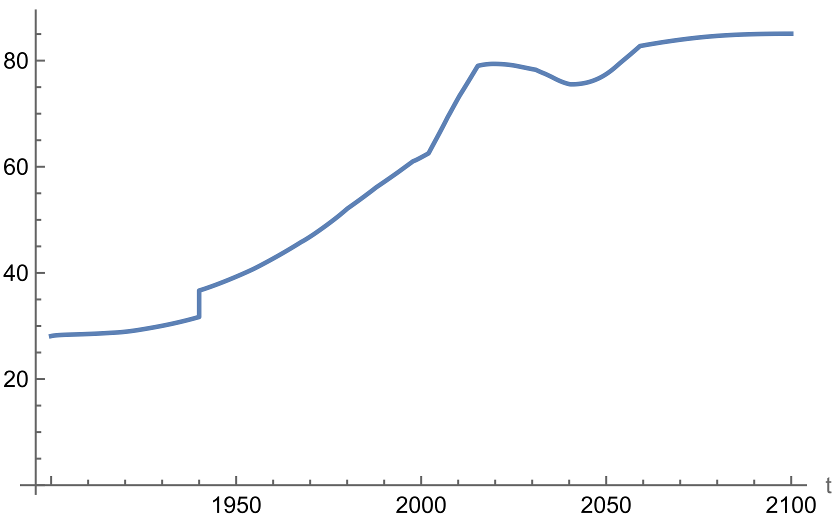

Figure 5. World average Life Expectancy (years) by time. *World3*, Benchmark Scenario 9. Horizontal axis is calendar year. Note that the life expectancy is constant starting about Year 2060. Compare with Figure 2 (from Benchmark Scenario 1).

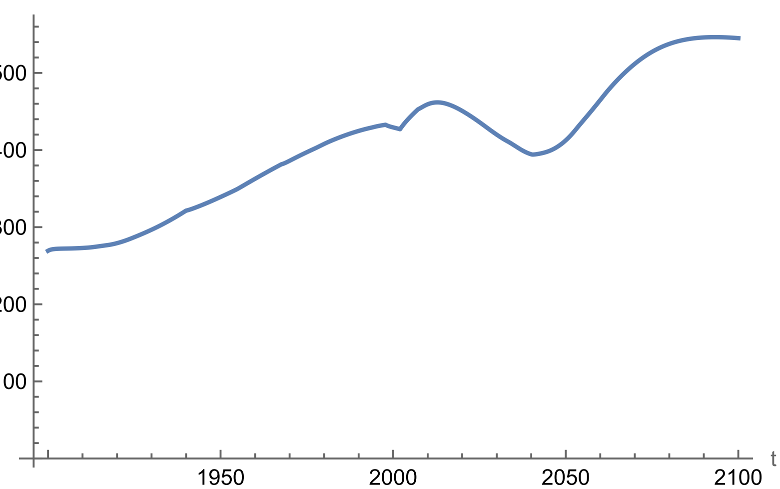

Figure 6. World food production (in vegetable-equivalent kilograms per person-year) by time. *World3*, Benchmark Scenario 9. Horizontal axis is calendar year. Note that food production is constant starting about Year 2080. Compare with Figure 3 (from Benchmark Scenario 1).

Summarizing the results shown in Figures 1 – 6 (and those in Horner (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 (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. For example, the world population has tended to increase exponentially but the resources required to sustain that population increase at best linearly. Over at least the last century, in particular, 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 nine Benchmark Scenarios, only Benchmark Scenario 9 avoids a population collapse and a precipitous drop in the global economy.

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. Section 3.3 identifies the *World3* system variables whose trajectories are reported in this study.

3.1. Platform

The version of *World3* used in this study is Cellier (2008) hosted under the *System Modeler/Mathematica (*Wolfram, 2019; Wolfram, 2023) framework. The configuration files for 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 (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.

3.2. Selection of parameters to vary

The approach used in the present study to investigate the effects, on population-resource dynamics of climate-change-induced variation in wheat production, requires a set of parameters in *World3* that can at least *bound* the effects of climate change on wheat production. In the present study, LYF, a parameter that in *World3* can be used only to modify land yield (represented by the *World3* system variable LY) was selected for this purpose. Here are some rationales for that choice.

Global temperature increase caused by increases in anthropogenic greenhouse-gases (GHGs, such as CO_2) can cause significant changes in wheat production (Balla et al., 2019; IPCC, 2022). The IPCC Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) are a set of climate pathways developed for the climate modeling community as a basis for long-term and near-term modeling experiments. The RCPs are the product of a collaboration among assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts. The resulting product forms a comprehensive data set with high spatial and sectoral resolutions for the period extending to 2100.

The temperature trajectory of RCP4.5 (NOAA, 2023) was selected for this study. RCP4.5 is a stabilization-without-overshoot pathway to a radiative forcing of 4.5 W/m^2 (~650 ppm CO_2 equivalent) at stabilization after 2100 (van Vuurren et al., 2011).

The optimum temperature over the entire wheat growing season for more than 90% of the wheat produced today lies between about 17 and 23 °C (Porter and Gawith, 1999, p. 25; Balla et al., 2019) RCP4.5 implies that, by 2080, the surface temperature in each of the planet's major wheat-production regions during a large fraction of the wheat growing season will exceed 29 °C. All else being the same, at 29 °C during the growing season, therefore, 100% of the production of today's dominant wheat varieties would be lost (Porter and Gawith, 1999, Table 1, p. 15, assuming normal distributions of the data in that Table; Balla et al., 2019).

The atmospheric CO_2 production rate implied by RCP4.5 would need to be halved within the next two decades to keep the temperature of the planet's major wheat-production regions within the heat tolerance of today's dominant wheat strains (NOAA 2023).

Within the range of values [0.7, 1.2], LYF allows the user to define variation in LY caused by *any* user-designated regime that is consistent with the intended application semantics (see Turner (2011) for a discussion of this term) of the rest of *World3*. More specifically, in *World3*, LY is calculated by multiplying LYF with other factors, as shown in Eq. 1. Eq. 1 is the *only* use of LYF in *World3* (Meadows et al. 1974, Eq. 103, p. 307; Cellier 2019):

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

where,

LY and LYF are as noted above

LFERT is a land fertility multiplier

LYMC is a land-yield multiplier from capital (investment)

LYMAP is a land-yield multiplier from air pollution

Because this study concerns the *reduction* of wheat production under the RCPs, the LYF values of interest lie in the range [0.7, 1.0]. If LYF = 1.0, Eq. 1 shows that LYF has no effect on the value of LY. If LYF = 0.7, LY is reduced by (100(1.0 – 0.7) =) 30%.

All else being the same, in *World3*, LY is proportional to food production (FP; see especially Eq. 87 in Meadows et al. (1974), p. 280). In *World3*, wheat accounts for approximately one-third (~30%) of FP (see for example Meadows et al., 1974, Figures 4-20 and 4-25; Shewry and Hey, 2015; Riaz et al., 2021). All else being the same, therefore, a 100% loss of wheat production is a 30% loss of FP, and that corresponds to a 30% reduction in LY. That fact allows us to use LYF = 0.7 (= 1.0 – 0.3) as a proxy for bounds on the effects on wheat production of the temperature trajectory of RCP4.5 in Year 2080. To reiterate, setting LYF = 1.0 corresponds to "the RCP4.5 Year 2080 temperature reduces wheat production by 0%", and setting LYF = 0.7 corresponds to "the RCP4.5 Year 2080 temperature reduces wheat production by 100%".

Because of the way *World3* is constructed, LYF, once set for a scenario, has a constant value for the duration of that scenario (in this study, that duration is Years 1900 - 2100). For example, if LYF were set to 0.7, LY, all else being the same, *World3* would multiply LY by 0.7 for *every year* from 1900 to 2100. In the "real" world, however, it is likely that the effect of RCP4.5 on land yield would vary over time. In *World3*, the best we can do to approximate the time-varying temperature effect of a dynamical climate model such as RCP4.5 on land yield is to assume that that temperature effect in the period 2025 – 2100 can be approximated by setting LYF to *some* value in the range [0.7, 1.0]. What the specific single value of LYF should be in order to produce a sufficiently realistic approximation of the effect of RCP4.5 on the *World3* trajectory during years 2025 - 2100, we can't know prior to running simulations. But we can vary the value of LYF within [0.7, 1.0], which will allow us compute the *sensitivity of World3 to that variation* (see for example Winsberg, 2010). Accordingly, in this study the value of LYF was set to each of {0.7, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0} for each of the scenario definitions selected for this study.

As an alternative to the parameter-variation-based approach used in the present work, one could explicitly model the relation between temperature and wheat production by modifying the *World3* software. That approach would require adding equations to *World3* that define the dynamical relationship between temperature and wheat production. Such an approach, however, would not yield *World3* as such. The resulting software would have to be re-calibrated and re-verified. The effort required to perform that re-calibration and re-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). Moreover, it is provably *impossible* for finite agents (such as humans) to verify that a given calibration/test regimen of *World3* is at least as comprehensive as another (Horner and Symons, 2019).

3.3. State variables reported in this study

By convention, the standard reporting of the results of Benchmark Scenarios 1-9 documents the trajectories of the 12 *World3* variables shown in Table 3.

Table 3. List of *World3* variables reported 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
Industrial Output
Labor Utilization
Consolidated Industrial Output Per Capita
Persistent Pollution
Non-renewable Natural Resources

Summarizing, for each of Benchmark Scenarios 1-9, the value of LYF was set, in turn, 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 12 *World3* variables shown in Table 3 was computed on the platform described in Section 3.1.

4. Results

The source code and results described in Section 3 were saved to a PDF file, available at Horner (2023).

Figures 1 – 6 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 Table 3 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}.

The results shown in Figures 7 - 12, together with Horner (2023), show the response, *within World3*, of population-resource variables in Table 3 to variation in LY caused by setting the values of LYF, in turn, to each of {0.7, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0}. The results strongly suggest that *none* of the policies of the Benchmark Scenarios can mitigate all of the population-resource effects of wheat-production loss due to RCP4.5. 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 (9 Benchmark Scenarios x 7 LYF values per Benchmark Scenario) documented in Horner (2023) was approximately 3 hours, corresponding to about 10^{14} machine-operations, on the platform described in Section 3.1.

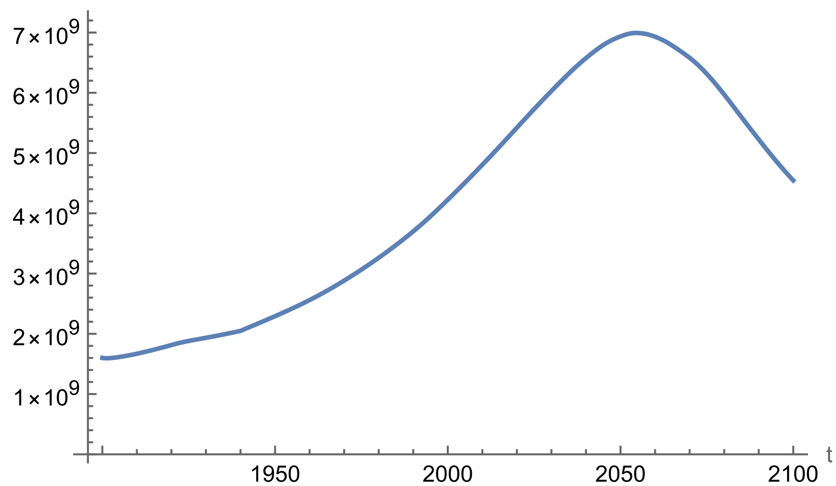

Figure 7. Population, people. Benchmark Scenario 1. **p_land_yield_fact_1** = 0.7. Horizontal axis is calendar year. Note the population collapse starting at about Year 2050. The peak population in this Figure is about 7 billion. Compare with Figure 1, in which **p_land_yield_fact_1** = 1.0, the peak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

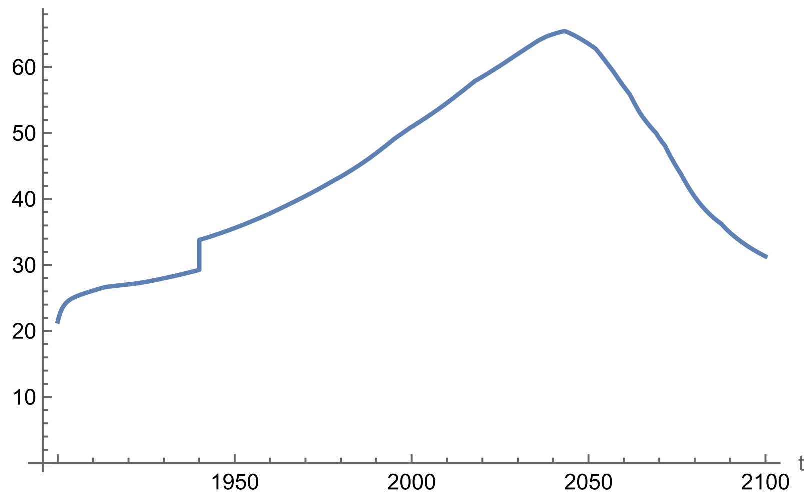

Figure 8. Life expectancy, years. Benchmark Scenario 1. **p_land_yield_fact_1** = 0.7. Horizontal axis is calendar year. Peak life expectancy (65 years) occurs at about Year 2045. Compare with Figure 2, in which peak life expectancy occurs at about 75 years in Year 2025. Note the life expectancy drop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

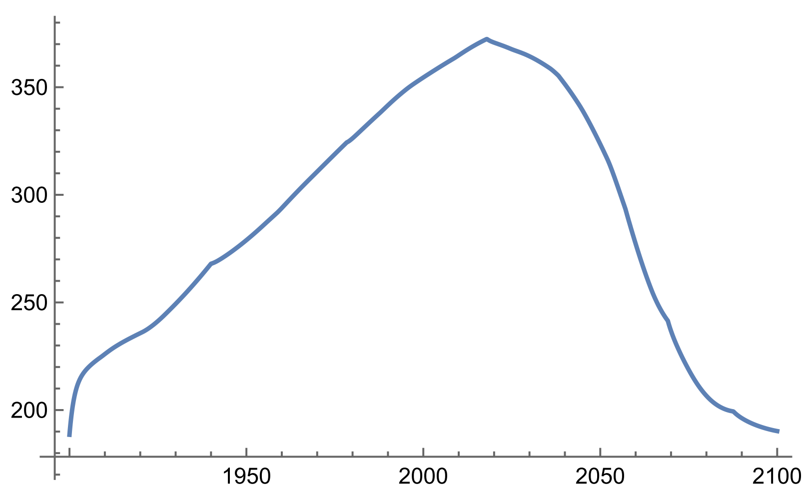

Figure 9. Food production, vegetable-equivalent kilograms per year per person. Benchmark Scenario 1. **p_land_yield_fact_1 = 0.7**. Peak production (about 380 vegetable-equivalent kilograms per year per person) occurs at about Year 2020. Horizontal axis is calendar year. Note the food production drop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

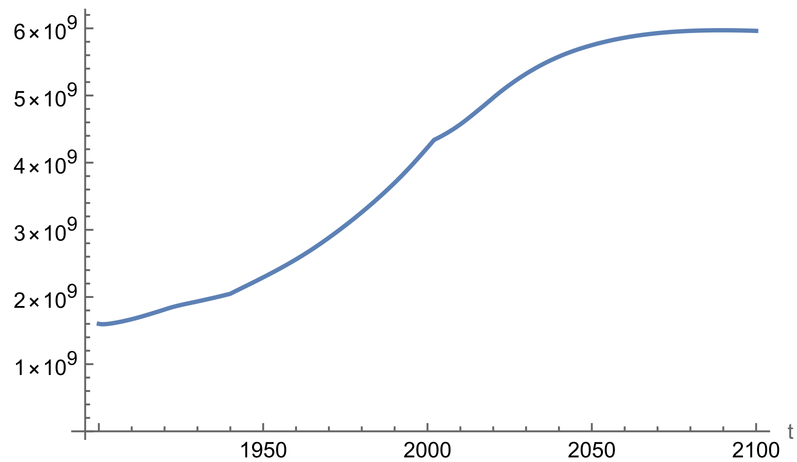

Figure 10. Population, people. Benchmark Scenario 9. **p_land_yield_fact_1** = 0.7. Horizontal axis is calendar year. Note that population remains approximately constant after Year 2050. Compare with Figures 4 and 7. Note in particular that the maximum population in Figure 10 is about 6 billion, whereas in Figure 4 it is about 8 billion, a 25% loss of peak population from the case in which **p_land_yield_fact_1** = 1.0.

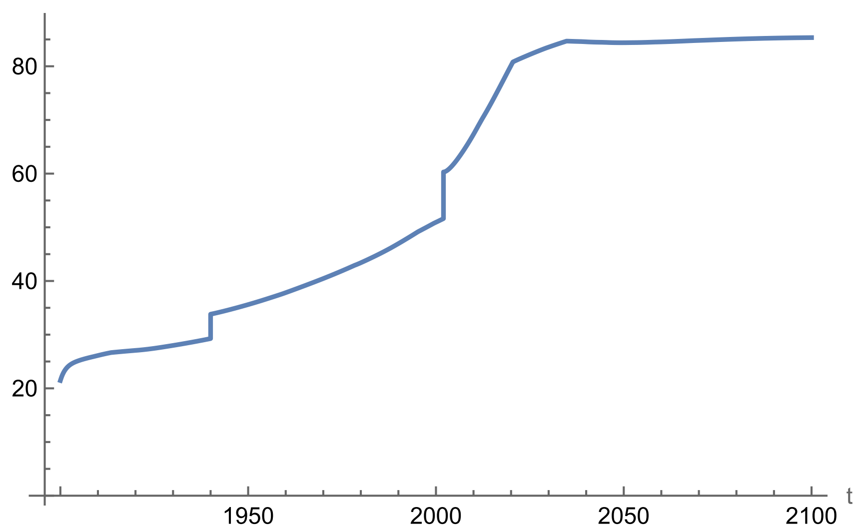

Figure 11. Life expectancy, years. Benchmark Scenario 9. **p_land_yield_fact_1** = 0.7. Horizontal axis is calendar year. Note that life expectancy is approximately constant after Year 2020. Compare with Figure 8.

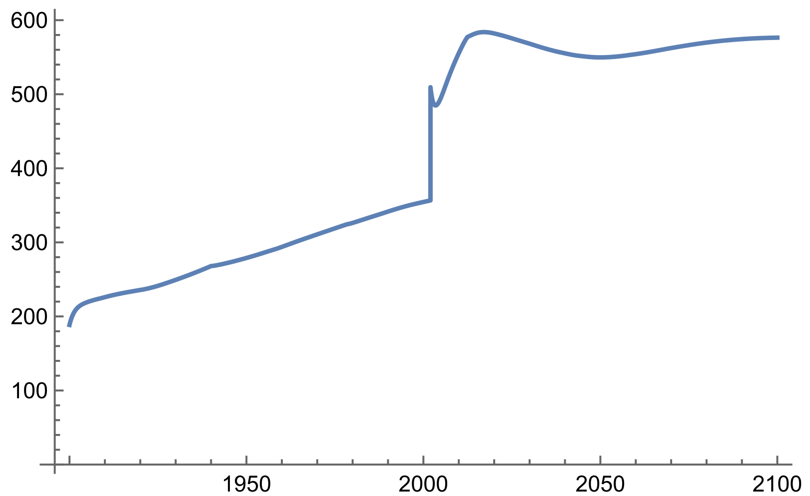

Figure 12. Food production, vegetable-equivalent kilograms per year per capita. Benchmark Scenario 9. **p_land_yield_fact_**1 = 0.7. Horizontal axis is calendar year. Note that food production is approximately constant after Year 2025. Compare with Figures 6 and 9. Note that the maximum food production per capita per year in Figure 12 is about 10% higher than the food production per capita per year in Figure 6 (in which **p_land_yield_fact_1** = 1.0, a somewhat counterintuitive result.)

5. Discussion

Using *World3* to help probe the interaction of human population-resource dynamics and wheat production is not a panacea: the effects of loss of wheat production on population-resource dynamics might lie outside what *World3* per se can plausibly represent. 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, p. 27; Balla et al., 2019). 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 wheat varieties is appealing, it glosses over at least three 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 exist now. Generally speaking, about one percent of each year's wheat crop must be saved for seed. Switching wheat varieties on the scale required to replace 2024 wheat production could easily take several years, even if 1% of each year's wheat crop were dedicated to growing seed for wheat varieties that could withstand the temperatures of RCP4.5 were grown for seed.

Second, any alternative to the currently dominant varieties of wheat would have to be tolerant of the entire temperature trajectory implied by RCP4.5 for the *entire* wheat growing season (Porter and Gawith, 1999, pp. 27-29; Balla et al., 2019).

Third, UN and *World3* estimates predict that, all else being the same, the food production required to sustain the world population in 2080 would require all of the arable land on the planet that is capable of growing wheat, assuming that wheat is produced at the rate equal to or greater than the rate of wheat varieties that dominate wheat production today. There are no varieties of wheat that can both (a) tolerate the temperature profile of RCP4.5 and (b) have a production rate as high as the varieties that dominate wheat production today.

Similarly, it has been suggested we could solve the loss of wheat production due to climate change by supplanting wheat with a cereal-grain other than wheat. In order to be testable (see for example Popper, 1986; Quine, 1961, especially Section 6), however, this hypothesis needs to specify what that alternative cereal grain could be. The probability of finding an alternative in the next few decades, is for all practical purposes zero, because there is no known cereal-grain alternative to wheat that can survive the temperatures predicted by RCP4.5 for Year 2080 and has at least the land yield of wheat (Wang et al., 2019).

In summary, the *World3* analysis reported in this paper strongly suggests that the population-resource effects of wheat-production loss from the temperature trajectory of RCP4.5 in Year 2080 would include a profound decrease in food and economic security through both direct and indirect population-dynamics pathways. In order to mitigate these effects, *World3,* together with IPCC (2022), imply that we must, over the next three to four decades

- i. halve the increase in atmospheric CO_2 posited by RCP4.5, presumably through the policies outlined in *World3* Benchmark Scenario 9, and/or
- ii. replace essentially all of the world's production of wheat with strains that
    - a. tolerate the temperature trajectory of RCP4.5
    - b. have yields at least as large as the dominant strains produced today.

Acknowledgement

This work benefited from discussions with Toufiq Siddiqi, Jorge Soberón, John Symons, Ramón Alvarado, Eric Winsberg, Anthony Pawlicki, Richard Stutzke, and Art Skidmore. For any infelicities that remain, I am solely responsible.

References

Balla, K., Karsai, I., Bónis, P., Kiss, T., Berki Z., Horváth, A., Mayer M., Bencze S. and Veisz, O. (2019), "Heat stress responses in a large set of winter wheat cultivars (*Triticum aestivum* L.) depend on the timing and duration of stress", *PLoS One,* Vol. 14 No. 9. https://doi.org/10.1371/journal.pone.0222639

Bardi, U. and Pereira, C. (Eds) (2022), *Limits and Beyond: 50 years on from The Limits to Growth, what did we learn and what's next? A Report to The Club of Rome,* Exapt Press.

Cellier, F.E. (2008), "*World3* in *Modelica*: creating system dynamics models in the *Modelica* framework", available at: https://inf.ethz.ch/personal/cellier/Pubs/World/modelica_08_*World3*.pdf (accessed 28 April 2019).

Cellier, F.E. (2019), "SystemDynamics.WorldDynamics.World3", available at: https://build.openmodelica.org/Documentation/SystemDynamics.WorldDynamics.*World3*.html (accessed 17 March 2019).

Ehrlich, P.R. and Ehrlich, A.H. (2009), "The population bomb revisited", *Electronic Journal of Sustainable Development*, Vol. 1, pp. 163-171.

Herrington, G. (2020), "Update to limits to growth: comparing the World3 model with empirical data", *Journal of Industrial Ecology*, Vol. 25, pp. 614-626. https://doi.org/10.1111/jiec.13084

Horner, J.K. (2022), "A World3 analysis of the sensitivity of population/resource dynamics to pandemic scale variation in life expectancy", *International Journal of Development and Sustainability*, Vol. 11 No. 11, pp. 348-366.

Horner, J.K. (2023), Supplemental Information for "A *World3* analysis of the response of population-resource dynamics to climate-change-driven loss of wheat production", available at: http://jkhorner.com/POPULATION_DYNAMICS/LYF_ALL_numbered.pdf (accessed 15 January 2025).

Horner, J.K., and Symons, J.F. (2019), "Why there is no general solution to the problem of software verification", *Foundations of Science* 3, pp. 541-557. https://doi.org/10.1007/s10699-019-09611-w

IPCC (2022), "Climate Change 2022: Impacts, Adaptation and Vulnerability", available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ (accessed 3 December 2024).

Malthus, T.R. (1798), *An Essay on the Principle of Population,* J. Johnson, London, England.

Meadows, D.H., Meadows, D.L., Randers, J. and Behrens, WW (III). (1972), *The Limits to Growth*, 2nd ed., The New American Library: New York, NY.

Meadows, D.H., Randers, J. and Meadows, D.L. (2004), *The Limits to Growth: The 30-Year Update,* Chelsea Green, White River Junction, VT.

Meadows, D.L., Behrens, WW III, Meadows, D.H., Naill, R.F., Randers, J. and Zahn, E.K.O. (1974), *Dynamics of Growth in a Finite World,* Wright-Allen Press, Cambridge, MA.

Nebel, A., Kling, A., Willamowski R. and Schell,T. (2023), "Recalibration of limits to growth: an update of the World3 model", *Journal of Industrial Ecology*, Vol. 28, pp. 87-99. https://doi.org/10.1111/jiec.13442

NOAA (2023), "Climate Model: Temperature Change (RCP 4.5) - 2006 – 2100", available at: https://sos.noaa.gov/catalog/datasets/climate-model-temperature-change-rcp-45-2006-2100/ (accessed 15 January 2025).

Nørgård, J.S., Peet J. and Ragnarsdottir, K.V. (2010), "The history of the limits to growth", *Solutions,* Vol. 1 No. 2, pp. 59-63.

OpenModelica Organization (2019), "OpenModelica", available at: https://www.openmodelica.org/ (accessed 28 April 2019).

Popper, K.R. (1986), *The Logic of Scientific Discovery*, Basic Books. New York, NY.

Porter, J.R. and Gawith, M. (1999), "Temperatures and the growth and development of wheat: a review", *European Journal of Agronomy*, Vol. 10, pp. 23-26. https://doi.org/10.1016/S1161-0301(98)00047-1

Quine, W.V.O. (1961), "Two dogmas of empiricism", in: W. V. O. Quine, *From a Logical Point of View*, Harper & Row, New York, New York.

Randers, J. (2012), *2052: A Global Forecast for the Next Forty Years,* Chelsea Green, White River Junction, VT.

Riaz, M.W., Yang, L., Yousaf, M.I., Sami, A., Mei, X.D. and Shah L. (2021), "Effects of heat stress on growth, physiology of plants, yield and grain quality of different spring wheat (*Triticum Aestivum* L.) genotypes", *Sustainability,* Vol. 13 No. 5. https://doi.org/10.3390/su13052972

Rosenzweig, C. and Iglesias, A. Ed.s. (1994), *Implications of Climate Change for International Agriculture: Crop Modeling Study,* US Environmental Protection Agency, Washington, D.C.

Roser, M. and Ritchie H. (2022), "Our World in Data: Food Supply", available at: https://ourworldindata.org/food-supply (accessed 1 September 2022).

Shewry, P.R. and Hey, S.J. (2015), "The contribution of wheat to human diet and health", *Food and Energy Security, Vol.* 4 No. 3, pp. 178-202. https://doi.org/10.1002/fes3.64

The Modelica Association (2019), "Modelica", https://www.modelica.org/ (accessed 28 April 2019).

Turner, G.M. (2008), "A comparison of The Limits to Growth with 30 years of reality", Global *Environmental Change,* Vol. 18, pp. 397-411. https://doi.org/10.1016/j.gloenvcha.2008.05.001

Turner, G.M. (2014), "Is global collapse imminent?", MSSI Research Paper No. 4, Melbourne Sustainable Society Institute.

Turner, R. (2011), "Specification", *Minds and Machines*, Vol. 21 No. 2, pp. 135-152. https://doi.org/10.1007/s11023-011-9239-x

United Nations, Department of Economic and Social Affairs, Population Division. (2019), "World Population Prospects: The 2019 Revision", https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0 (accessed 10 August 2022).

van Vuuren, D.P., Edmonds, J., Kainuma, M., Miahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. (2011), "The representative concentration pathways: an overview", *Climatic Change* (2011) Vol. 109, pp. 5-31, https://psl.noaa.gov/ipcc/cmip5/rcp.pdf (accessed 15 January 2025). https://doi.org/10.1007/s10584-011-0148-z

Wang, J., Vanga, S.K., Saxena R., Orsat V. and Raghavan V. (2019), "Effect of climate change on the yield of cereal crops: a review", *Climate*, Vol. 6 No. 2, p. 41. https://doi.org/10.3390/cli6020041

Winsberg, E. (2010), *Science in the Age of Computer Simulation*, University of Chicago Press, Chicago, Illinois.

Wolfram Research (2019), "System Modeler v12.0", available at: https://www.wolfram.com/SystemModeler/ (accessed 24 March 2019).

Wolfram Research. (2023), "Mathematica v13.3 Home Edition", available at: https://www.wolfram.com/mathematica-home-edition/ (accessed 15 March 2023).