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Research Article

Human Population Collapse Ahead: A Comparison of Demographic and System Dynamics Approaches

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The modeling of human population trends has followed two distinct methodological traditions. Standard demographic models, exemplified by United Nations projections, employ extrapolation techniques based on historical fertility and mortality trends. These models typically yield smooth transitions to stable or slowly declining populations. System dynamics models, initiated by Forrester's *World Dynamics*[1] and *The Limits to Growth*[2], treat population as a stock within a complex system dominated by feedbacks created by industrial capital, agricultural production, resource depletion, and pollution. This paper compares these two established traditions. While demographic models generally project global population peaking close to or higher than 10 billion by 2080–2100 with gradual stabilization or subsequent decline, system dynamics models — particularly those in the World3 lineage — generally generate earlier peaks (2030–2060), more rapid subsequent declines, and potential non-linear collapse trajectories consistent with the "Seneca Effect"[3], which describes how decline is often faster than prior growth in complex systems. I assess the structural assumptions underlying these differences and evaluate current empirical evidence bearing on their validity. A case study presented here is that of Ireland at the time of the Great Famine, where the population followed a trajectory unpredictable by conventional demographic models, used to illustrate how endogenous feedback dynamics can shape the demographic response to an exogenous shock even though the shock's timing itself remains unpredictable.

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1. Introduction

The question of future human population trajectories has generated substantial scientific and policy interest, yet approaches to this question remain methodologically based on scarcely compatible modeling choices. The dominant paradigm used by the United Nations and national demographic projections treats population dynamics as primarily determined by fertility transition processes observable in historical data and extrapolated to the future. An alternative paradigm, rooted in system dynamics and general systems theory, treats population as one of the stock variables within a complex, resource- and pollution-constrained system characterized by multiple feedback loops, delays, and non-linearities. Other modeling choices are also possible.

This methodological divergence has produced systematically different predictions. Understanding these differences is not merely of academic interest: population projections inform climate policy, resource planning, and sustainable development goals[4]. If the system dynamics perspective captures essential features of global socio-ecological dynamics better than demographic models, current policy frameworks may be inadequately prepared for plausible future trajectories.

This paper focuses on demographic and system dynamics models as the two most established and long-standing traditions in population projection. A third, increasingly active family of approaches — agent-based models (ABM) and data-driven / machine-learning methods — is discussed in Section 3.1 as complementary lines of inquiry.

2. The Demographic Modeling Tradition

Standard cohort-based demographic projections are commonly used, for instance, by the United Nations Population Division, the Wittgenstein Center, and the Institute for Health Metrics and Evaluation (IHME), and others. In these models, population is disaggregated by age and sex; future population is computed by projecting age-specific fertility rates, mortality rates, and migration flows based on historical trends and assumed transition patterns[5]. The central theoretical framework is the demographic transition theory. It assumes that societies progress from high-fertility/high-mortality regimes through intermediate stages

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to low-fertility/low-mortality equilibria. Projection variants typically assume fertility converges to replacement level or slightly below, generating smooth logistic-like trajectories.

When applied in its most common, deterministic form, the cohort-component method treats population as the dependent variable of fertility choice and mortality improvement, not as an interactive component of a biophysical system. Some of these effects are partially reflected, implicitly, in the historical data used for calibration, and some scenario variants now represent them explicitly; but the baseline projections most widely cited and used for policy purposes typically still assume:

- Longer life expectancies regardless of environmental stress
- Migration projections that do not systematically incorporate climate-induced displacement
- No effect of climate change on food production and fertility
- No mineral depletion and energy shortages
- No water supply shortages
- No effects of extreme weather phenomena
- Constant institutional stability and no wars

The UN World Population Prospects of 2022 (medium variant) projects a peak population of approximately 10.4 billion in 2086, and a population of 10.3 billion in 2100. The decline rate is typically modeled as very gradual, approximately 0.1–0.3% annually. A projection by the same methods[6] suggests an earlier peak (~9.7 billion in 2064) and faster decline, but still within a gradual framework.

This is a synthetic description of the field of demography as it is generally understood today. In this field, we can also detect a movement toward methods more complex than the single deterministic cohort-component method. Bayesian probabilistic projections[7] now underpin the UN's official uncertainty intervals, and Shared Socioeconomic Pathways[8] explicitly build scenario branches incorporating divergent assumptions about migration, climate impacts, and institutional stability. These extensions relax some of the rigidities discussed below and address part of the concern raised in this review. Even so, these methods remain fundamentally extrapolative: they draw scenario uncertainty from ranges of historically observed parameters rather than from an explicit mechanistic coupling to resource, pollution, or capital dynamics. It is this structural feature — not the absence of any uncertainty treatment — that distinguishes the demographic tradition from the system dynamics tradition discussed in Section 3.

3. The System Dynamics Approach

System dynamics (SD) was developed mainly by Jay Forrester in the 1960s on the basis of modeling complex systems using stocks, flows, and feedback loops as basic building blocks, from which system-level dynamics emerge[9]. *World Dynamics*[1] was the first application of system dynamics that aimed at modeling the integrated world system, including the human economy, natural resources, pollution, and population.

The Limits to Growth study[2] improved on Forrester's model with a more detailed structure and more extensive data. The authors developed a complete world model called "World3," based on five main stocks: population, industrial capital, agricultural capital, non-renewable resources, and pollution. Forrester's study and the Limits to Growth report were the first attempt ever to model the world's global population in a fully integrated biophysical model.

Key structural features included:

- Capital–population feedbacks: Industrial output per capita affects mortality and fertility; population growth drives capital investment needs
- Resource constraints: Non-renewable resource depletion increases capital costs for extraction
- Pollution dynamics: Industrial and agricultural outputs generate pollution stocks affecting health and agricultural productivity
- Agricultural limits: Land availability, erosion, and technology determine food production

The "standard run" or "base case" World3 scenario used the best data available in 1972 and assumed no change in the way the economic system was managed. It generated a population peak around 2050–2060 at about 10 billion people. The results are shown in Figure 1.

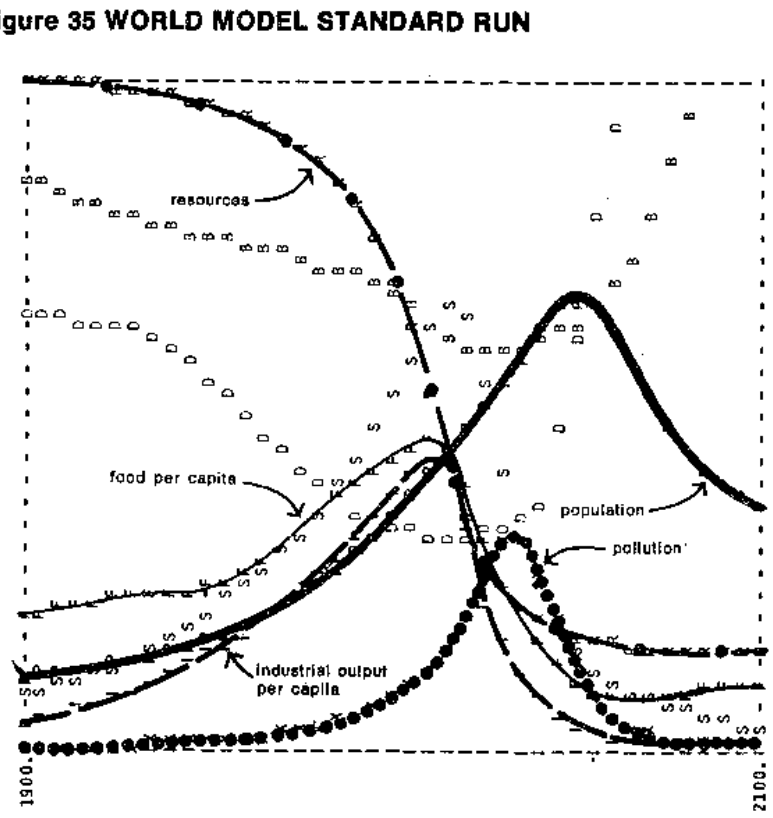

Figure 1. *The results of the "base case" scenario of the 1972 version of The Limits to Growth[2]. In this scenario, the population peak occurs in 2060 at ca. 10 billion people. Image courtesy of Dennis Meadows.*

In the 1972 study, the World3 model was still in an early stage of development, and its treatment of the population stock suffered from questionable assumptions. In particular, the authors supposed that the collapse of industrial and agricultural production would push fertility trends toward past conditions in which society was experiencing similar degrees of economic output — in other words, that fertility would return to the high values of the "baby boom." The result was that the model generated a base case scenario in which global population would keep growing for about four decades after the collapse of industrial and agricultural production.

This view was clearly unrealistic. The historical baby boom affected countries experiencing rapid economic growth, such as the US in the 1950s and 1960s. The increase in fertility was based on people's expectations of a better future for their offspring. In a declining economy, it is hard to expect that people would react by having more children. Indeed, the historical data for the countries of the former Soviet Union that collapsed in 1991 show that fertility decreases with economic decline.

Updated versions of the World3 model[10][11] refined data and equations, preserving core structural assumptions but incorporating a more realistic negative effect of economic decline on fertility. These updates generated earlier population peaks. Independent SD models[12][13][14] tested World3 against empirical data, generally finding historical trajectories tracking the "standard run" or "comprehensive technology" scenarios of The Limits to Growth series.

To illustrate this updated parameter set directly, Figure 2 shows the standard run (Scenario #1, “Business as usual”) of World3-03 — the model structure and 2003-updated parameter set underlying Meadows, Randers & Meadows[11] — computed using the open-source pydynamo-w implementation (Baucher[15], built on Vanwynsberghe’s pyworld3). As in the original published figure, each of the five state variables is normalized to its own [0,1] range over 1900–2100 rather than sharing a common numerical y-axis; no other parameters were altered from the software's default Scenario #1 definition.

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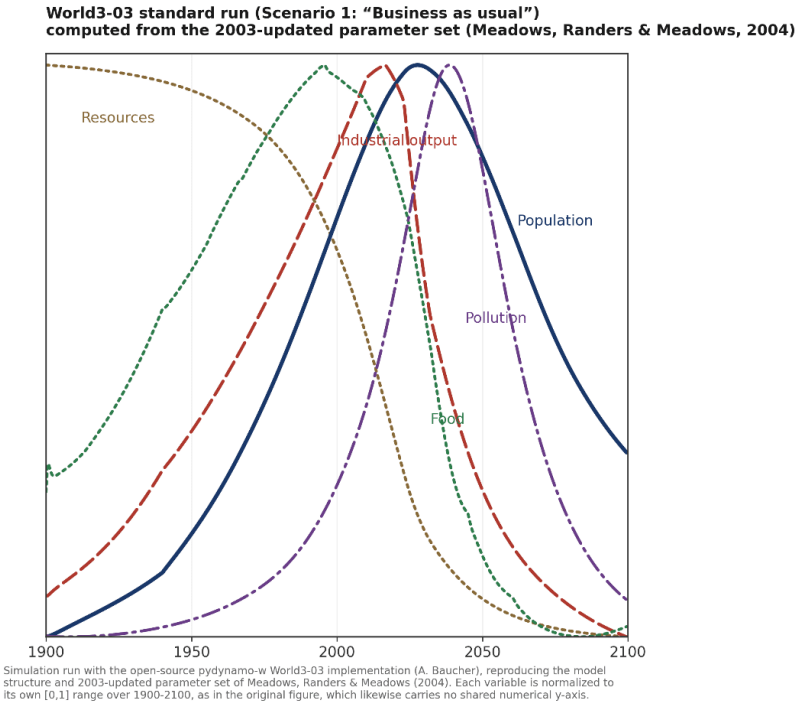

Figure 2. *World3-03 standard run (Scenario #1: “Business as usual”), computed from the 2003-updated parameter set of Meadows, Randers & Meadows[11] using the open-source pydynamo-w implementation. This is genuine simulation output, not a digitization or approximation of the published figure; the population peak falls at 2027.5, consistent with the timing shown in the published 2004 figure.*

Some SD model configurations generate asymmetric collapse trajectories for industrial and agricultural output, where decline proceeds faster than prior growth. This is known as the "Seneca Effect" or "Seneca Cliff"[3][4]. An example is shown in Figure 3, from the 1972 version of *The Limits to Growth*.

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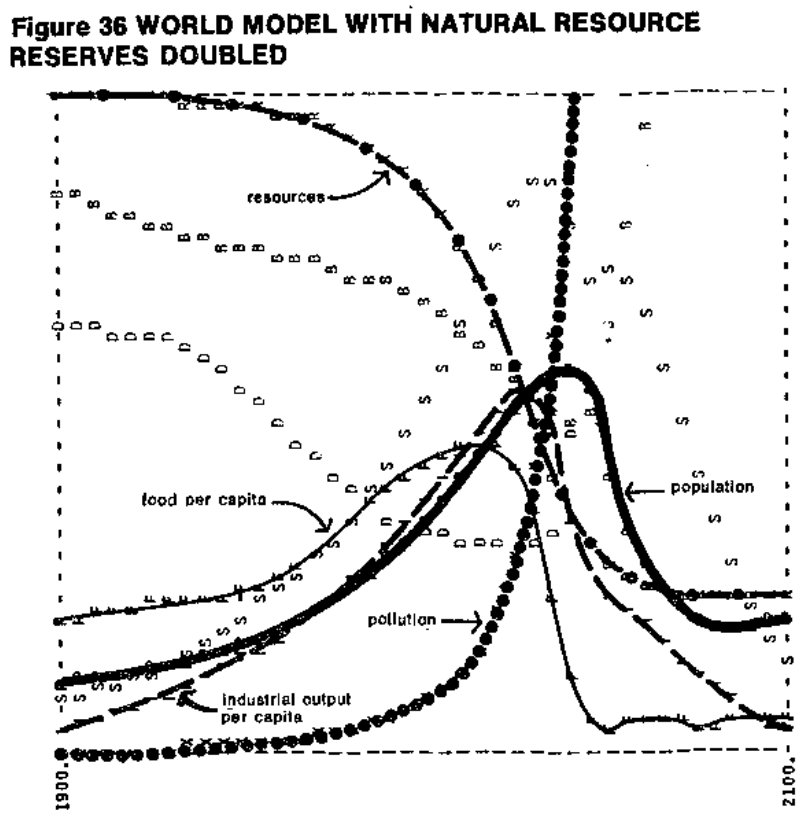

Figure 3. *Scenario n. 2 of The Limits to Growth*[2]*. In this case, natural resources are assumed to be double those estimated in 1972. The population peak occurs at approximately 2050 at a population of approximately 13 billion. Compared with the base case, the collapse occurs earlier and for a larger population. Note the Seneca shape resulting from the effect of skyrocketing pollution, which may be interpreted as a proxy for global warming. Image courtesy of Dennis Meadows.*

This result emerges from:

- Capital depreciation lags: Industrial capital cannot be maintained as resource extraction costs rise
- Pollution threshold effects: Non-linear health and agricultural impacts from the costs of pollution abatement
- Network collapse: Interdependent system components failing in cascade
- Debt and economic complexity: Financial system instabilities under resource constraint

The Seneca Effect appears in World3 scenarios with strict resource limits or high pollution sensitivity, generating population decline rates of 1–2% annually — far exceeding demographic model projections. It should be noted that this pattern is best documented within the World3 family of models specifically; other SD-based studies of collapse dynamics in coupled human-natural systems — e.g., Dockstader, Bauch & Anand[16] on interconnected socio-ecological metapopulations — find qualitatively similar early, sharp declines driven by network and feedback effects, but have not been calibrated against global human population data specifically, leaving open how directly their conclusions transfer to the present comparison.

3.1. Beyond Two Paradigms: Agent-Based and Data-Driven Approaches

The comparison developed in this paper can be discussed within a broader methodological landscape. Among the alternatives, agent-based modeling (ABM) is a process-based approach distinct from system dynamics in its bottom-up, individual or small-scale level representation of behavior rather than SD's top-down stock-and-flow aggregation. ABMs of population and migration dynamics can, in principle, generate collapse-like trajectories through mechanisms analogous to SD modeling, although involving network effects, heterogeneous agent decision rules, and spatial interactions which are largely invisible to both cohort-component demography and aggregate SD models. As of this writing, ABM applications to global-

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scale, long-run population trajectories remain comparatively rare and immature. This is an area where future comparative work is best positioned to make progress.

A third, rapidly growing family of approaches uses statistical and machine-learning methods to fit flexible, non-parametric functions to demographic and environmental data[17]. These methods share the empirical, data-fitting character of standard demographic models — they remain bound to patterns observed in the historical record — while relaxing some of the structural rigidity of the cohort-component method itself. They are a promising bridge between the two traditions compared here, but, like ABM applications to this problem, they inherit the general limitation of empirical models discussed in Section 2.

Finally, the demographic tradition itself is increasingly incorporating stochastic and Bayesian methods that improve resolution on migration — the most volatile component of population changes at fine spatial and temporal scales — and draw on multiple data sources to quantify forecast uncertainty explicitly (see Section 2). Closer engagement between these methodological communities, rather than treatment of demographic and system dynamics models as a binary choice, is likely to be the most productive path forward; this point is revisited in the Conclusion.

4. A Case Study: Ireland's Great Famine

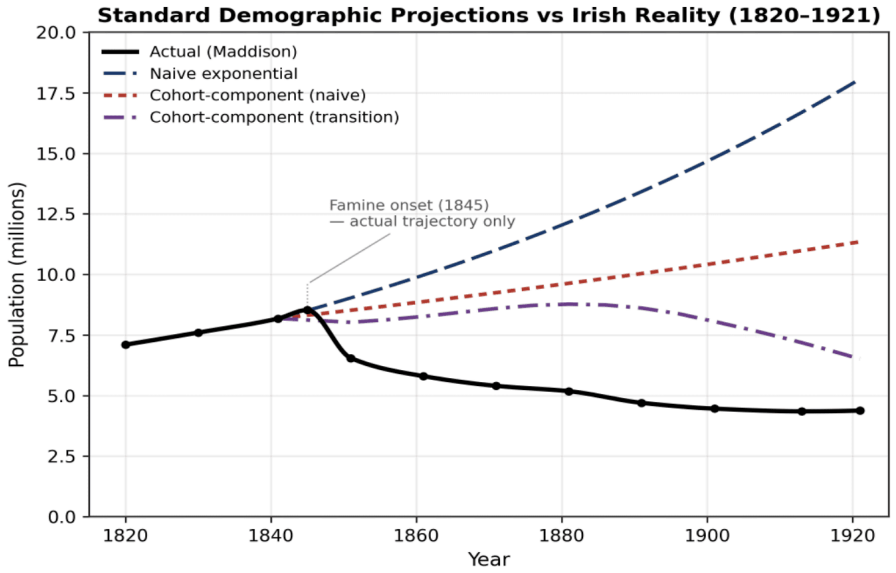
The case of Ireland's Great Famine provides a good example of how demographic models can miss a rapid population decline. The famine that struck Ireland in 1845 was triggered by a failure of the potato crops, but, in reality, the turning point was the result of a consistent pattern of overexploitation and overpopulation. After 1845, several years of poor harvests led to a rapid population collapse caused by hunger, disease, and emigration. The data are shown in Figure 4.

The question that may be asked of these data is what modern demography could have said if it had been available before the Great Famine. This question can be examined by developing simple demographic models. Here, I compare two approaches: the cohort-component method that is standard in demography, and a method based on system dynamics.

4.1. The Cohort-Based Analysis

Historical population data for Ireland were compiled from census records and the Maddison Project Database. For the cohort-component analysis, the 1841 population of 8.18 million was distributed across seventeen five-year age groups using the stable age structure implied by the model's fertility and survival schedules. The baseline schedule corresponded to a total fertility rate of 5.65, age-specific survival probabilities ranging from 0.75 in the youngest transition to 0.15 in the terminal 80+ group, and net migration of -20 per 1,000 population per five-year period. In the naive projection, these parameters were held constant; in the transition scenario, fertility declined progressively, survival improved, and net migration was increased during and after the famine period.

The results for a standard cohort-based model are shown in Figure 4; the full methodology and verified code are given in the Supplementary Material.



Naive exponential and cohort-component curves computed from a single verified script (Kimi/Claude, cross-checked, with the 1841 age structure corrected to the stable distribution implied by the model's own vital rates); actual trajectory interpolated through known anchor points, incl. verified 1841-1921 data.

Figure 4. *Cohort-based demographic projection methods applied to Irish population data (1820–1921). The solid black line shows the historical trajectory (Maddison Project data plus known pre-famine and post-famine anchor points); the famine-onset marker applies to this actual trajectory only. Lines show three standard demographic projections — naive exponential, cohort-component (naive), and cohort-component (transition) — all assuming parameter continuity from 1841 onward and none modeling the famine itself. The cohort-component curves use an initial age structure corrected to the stable distribution implied by the model's own vital rates (see Supplementary Material), which grow smoothly and consistently with Ireland's actual pre-famine trend. All curves are generated from a single verified script.*

As expected, no simple cohort-based demographic model could have hinted at the possibility of a disaster such as the Great Famine. Translated to our current situation, this means that in a similar scenario, our current demographic models could lead to unjustified optimism regarding population trajectories.

Method	1901 Projection	Error vs Actual
Naive Exponential	14.82 M	+232%
Cohort-Component (Naive)	10.45 M	+134%
Cohort-Component (Transition)	8.06 M	+81%
Actual Historical	4.46 M	—

Table 1. Demographic projection errors for 19th-century Ireland (1901 projections vs actual).

A demographer in 1841 extrapolating from current conditions would have projected anywhere from 8.1 million (cohort-component, transition-aware) to nearly 15 million (naive exponential) by 1901; the actual population was 4.46 million. The failure stems from the models' inability to anticipate:

- Exogenous shocks: Potato blight (biological contingency)
- Structural regime change: The "Irish marriage pattern" (late marriage, high celibacy)
- Cultural institutionalization: Mass emigration as normalized behavior
- Feedback dynamics: Population decline → land consolidation → further emigration

4.2. The SD Approach

Could a system dynamics model have predicted the Irish population collapse? Plausibly, current models would have proposed a much less optimistic trajectory on the basis of an approach that explicitly models

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feedback mechanisms (e.g., population pressure → land scarcity → emigration → reduced marriage rates). To test this approach, a fitting of the Irish historical data was performed using the standard Seneca model[3].

For this analysis, annual Irish population estimates for 1820–1913 from the Maddison Project Database[18] were fitted using a three-variable dynamical system representing a renewable resource stock, population, and an accumulated stress stock. Population was normalized to the historical peak, and the nine free model parameters were estimated by minimizing the sum of squared residuals between simulated and observed population using a multi-start adaptive Nelder–Mead procedure. The differential equations were integrated using the LSODA solver. Because the smooth endogenous model could not reproduce the abrupt famine collapse, the 1845–1847 potato-blight shock was represented as an exogenous temporary reduction in effective carrying capacity to 10% of its baseline value, after which carrying capacity was restored while the remaining model parameters were kept unchanged. Full equations, parameter values, and computational details are provided in the Supplementary Material.

As shown in Figure 5, a pure Seneca model could generate a rapid decline in correspondence to the Great Famine, but it could not generate the historical abrupt collapse. Only an *ad hoc* assumption of a rapid shock generated by two years of poor harvest could fit the curve. Of course, a hypothetical system dynamics user operating in the 1840s would have had no way to know that a disastrous famine would strike in 1845. However, they would know that other famines had struck Ireland in earlier times, and the Seneca model could have been used as a qualitative guide to imagining a possible future.

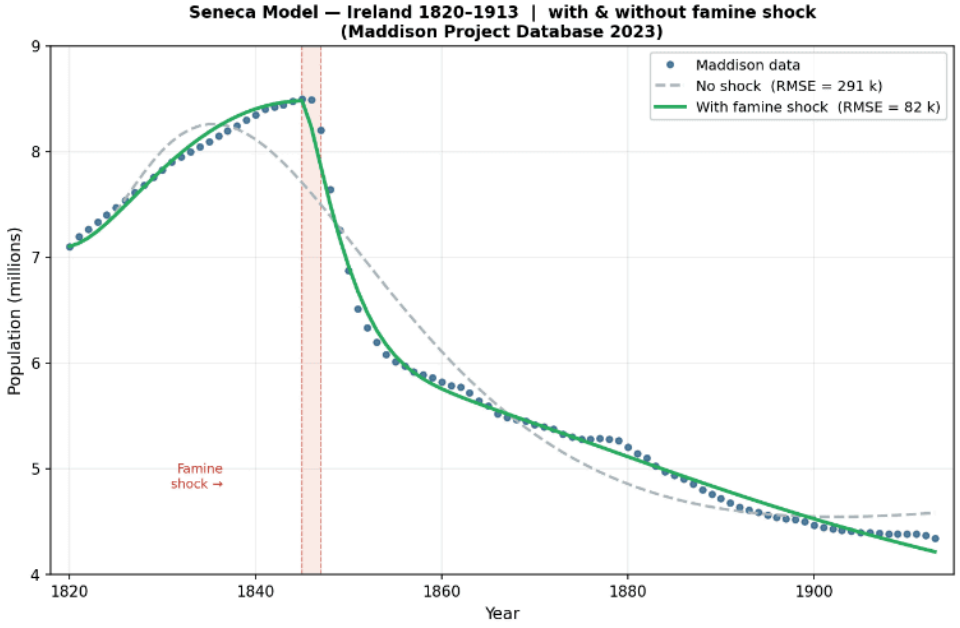

Figure 5. *The Irish population data at the time of the Great Famine fitted with a standard Seneca Model[3]. Dots: historical data. Gray dashed line: no famine shock. Green line: famine shock in 1845-1847. See the Supplementary Material for details.*

5. Critical Assessment

It is worth distinguishing two analytically separate questions that the Irish case raises. The first is whether the timing of the initiating shock — the potato blight of 1845 — could have been predicted by either modeling tradition. It could not be, at least in terms of establishing a specific date. The stress on the Irish food production system was known, just as the fact that periodic famines hit the country in previous times. Hence, a new shock could be expected, but its precise time was beyond the capabilities of both kinds of population models, demographic or system-dynamic.

The second, analytically distinct question is whether either tradition could have anticipated the magnitude and duration of the demographic response once the shock occurred — the sustained, multi-decadal depopulation running through 1913, some 66 years after the blight itself. It is this second question that the Seneca-model fit addresses, and where the two traditions diverge sharply: cohort-component methods, by construction, assume the shock's effects dissipate as parameters revert toward their pre-

shock trajectory, whereas a model built around an accumulating stress stock can represent a shock's effects compounding and persisting long after the triggering event has passed. This is the paper's central methodological point.

Demographic models have successfully predicted near-term (10–20 year) population changes but failed to anticipate major transitions (e.g., rapid fertility declines in Iran, fertility stalls in sub-Saharan Africa). System dynamics models have tracked aggregate behavior, but with significant uncertainty in timing and sectoral distribution.

Feature	Demographic Models (UN)	System Dynamics (World3 and derived models)
Peak timing	2080–2100	2030–2060
Peak magnitude	9–11 billion	8–12 billion
Post-peak decline rate	0.1–0.3%/year	0.5–2.0%/year
Trajectory shape	Symmetric	Symmetric/Asymmetric
Primary constraints	Fertility choice	Resource/pollution feedbacks
Climate effects	Exogenous scenario	Endogenous feedback

Table 2. Comparative Summary of Modeling Approaches

Recent developments partially support SD structural concerns:

- Resource constraints: Tight oil and gas have delayed fossil fuel peaks, but at increasing environmental and economic cost
- Pollution impacts: Climate change effects on agricultural yields and heat mortality are emerging faster than demographic models assumed
- Economic fragility: The 2008 financial crisis and COVID-19 demonstrated system interdependencies and cascade risks
- Fertility declines: Global fertility is falling faster than UN medium variants projected[5], suggesting non-linear social responses to economic and environmental stress

A further limitation concerns the sensitivity of global SD trajectories to parameter choices and structural assumptions about feedback loops. This is a legitimate concern for any model of this level of complexity. Independent replications[12][13][14] have subjected the World3 family to substantial empirical and, in the case of Nebel et al., structural-sensitivity testing, generally finding the qualitative shape of the "standard run" and "comprehensive technology" trajectories to be robust across a range of parameter perturbations, even as exact peak timing and magnitude vary. A fully independent global sensitivity and uncertainty analysis specific to the present comparison, however, is beyond the scope of this paper and is flagged here as a direction for future work rather than a claim made on the basis of new analysis presented here.

The divergence between approaches reflects profound differences in fundamental assumptions. Demographic models assume continuity and adaptive capacity; system dynamics emphasizes fragility and threshold effects. Current evidence does not definitively favor either. If system dynamics captures essential features of global socio-ecological dynamics that demographic models omit, current policy frameworks assuming gradual demographic transitions may be insufficiently prepared. Rather than a forecast, the following is offered as a precautionary orientation consistent with that possibility, distinct from a claim that it will occur:

- Accelerated investment in renewable energy and agricultural resilience
- Health system strengthening for climate and pollution impacts
- Economic restructuring for potential rapid degrowth scenarios

6. Conclusion

The two main modeling traditions for human population dynamics generate systematically different predictions due to different conceptualizations of the human–Earth system. Demographic models project gradual transitions based on historical fertility patterns; system dynamics models generate earlier peaks and potential rapid declines through resource and pollution feedbacks.

A recurring pattern in system dynamics research — particularly across the World3 lineage, earlier peaks (2030–2060), lower peak magnitudes (typically 8–10 billion, although larger in some earlier models), and

potential Seneca-type decline trajectories — stands in marked contrast to demographic consensus. Recent empirical trends, including faster-than-projected fertility declines and emerging climate impacts on health and agriculture, suggest the divergence may resolve within the coming decades, potentially validating the system dynamics concern that biophysical constraints will override purely demographic transitions.

Given the stakes involved, methodological pluralism and precautionary planning for rapid transition scenarios remain scientifically warranted. The history of complex system collapses — from ancient civilizations to modern economic crises — suggests that asymmetric, rapid declines are not merely theoretical possibilities but recurring features of complex systems termed "civilizations." Whether the current global civilization can avoid such trajectories depends critically on recognizing the potential for non-linear dynamics that mainstream demographic models, by their structural design, cannot capture.

The two traditions compared here are better understood as complementary than as competitors. Demographic models, especially in their Bayesian and scenario-based forms, retain a clear advantage for short- to medium-term, high-resolution projections, particularly where migration is the dominant source of change. System dynamics models retain an advantage for identifying qualitative long-term regime shifts driven by biophysical feedbacks that lie outside the historical calibration data available to purely empirical methods. Closer engagement between the demographic and system dynamics research communities — and further testing against agent-based and data-driven approaches, as discussed in Section 3.1 — is likely to sharpen both traditions more than treating this as a binary choice between them. This remains, at present, a hypothesis under active empirical scrutiny rather than an established conclusion.

Statements and Declarations

Funding

No specific funding was received for this work.

Potential Competing Interests

No potential competing interests to declare.

Data Availability

The historical population data used in this study were obtained from census records and the Maddison Project Database, as described in the manuscript and Supplementary Material. Methodological details and the code used for the cohort-component analysis are provided in the Supplementary Material. The Seneca-model equations, fitting procedure, and fitted parameter values are also reported in the Supplementary Material. Additional data and computational materials are available from the corresponding author upon reasonable request.

Author Contributions

U.B. was the sole author and is responsible for all aspects of the manuscript.

Use of Generative AI

Generative AI tools, specifically Anthropic's Claude Sonnet 4.6 and Moonshot's Kimi, were used to support critical review of the manuscript and to assist with the computational implementation and fitting calculations described in the study. The author reviewed and verified the resulting analyses and outputs and takes full responsibility for the accuracy, integrity, and conclusions of the work.

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Supplementary data: available at https://doi.org/10.32388/U2SNY9.2

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