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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 approaches and their divergent predictions. 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 consistently generate earlier peaks (2030–2060), more rapid subsequent declines, and potential non-linear collapse trajectories consistent with the "Seneca Effect"[3] (decline faster than prior growth). 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.

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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 incompatible frameworks. The dominant paradigm used by the United Nations and national demographic projections treats

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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.

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 that demographic models omit, current policy frameworks may be inadequately prepared for plausible future trajectories.

2. The Demographic Modeling Tradition

Standard demographic projections, as developed by the United Nations Population Division, the Wittgenstein Center, and the Institute for Health Metrics and Evaluation (IHME), rely on the cohort-component method. Population is disaggregated by age and sex; future states are 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 to low-fertility/low-mortality equilibria. Projection variants typically assume fertility converges to replacement level or slightly below, generating smooth logistic-like trajectories.

Demographic models treat population as the dependent variable of fertility choice and mortality improvement, not as an interactive component of a biophysical system. This creates unrealistic assumptions such as:

- Longer life expectancies are assumed regardless of environmental stress
- Migration projections 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 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 gradualist framework.

3. The System Dynamics Approach

System dynamics (SD) was developed mainly by Jay Forrester in the 1960s on the basis of modeling complex systems by means of stocks, flows, and feedback loops[7]. *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. 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" 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.

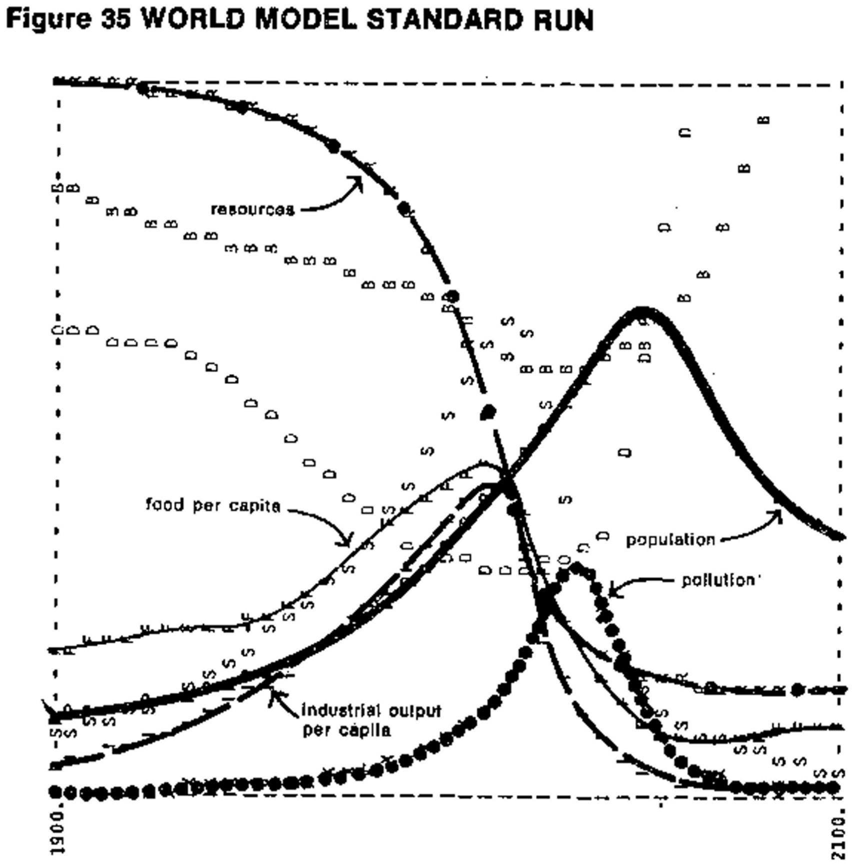

Figure 1. *The results of the "base case" scenario of the 1972 version of The Limits to Growth*[2]*. In this scenario, the population peak occurs in 2060 at ca. 10 billion people. Image courtesy of Dennis Meadows.*

The 1972 version of World3 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 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[8][9] 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[10][11][12] have tested World3 against empirical data, generally finding historical trajectories tracking the “standard run” or “comprehensive technology” scenarios of *The Limits to Growth* series.

Some SD model configurations generate asymmetric collapse trajectories for industrial and agricultural output, where decline proceeds faster than prior growth — the “Seneca Effect” or “Seneca Cliff”[3][4]. 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.

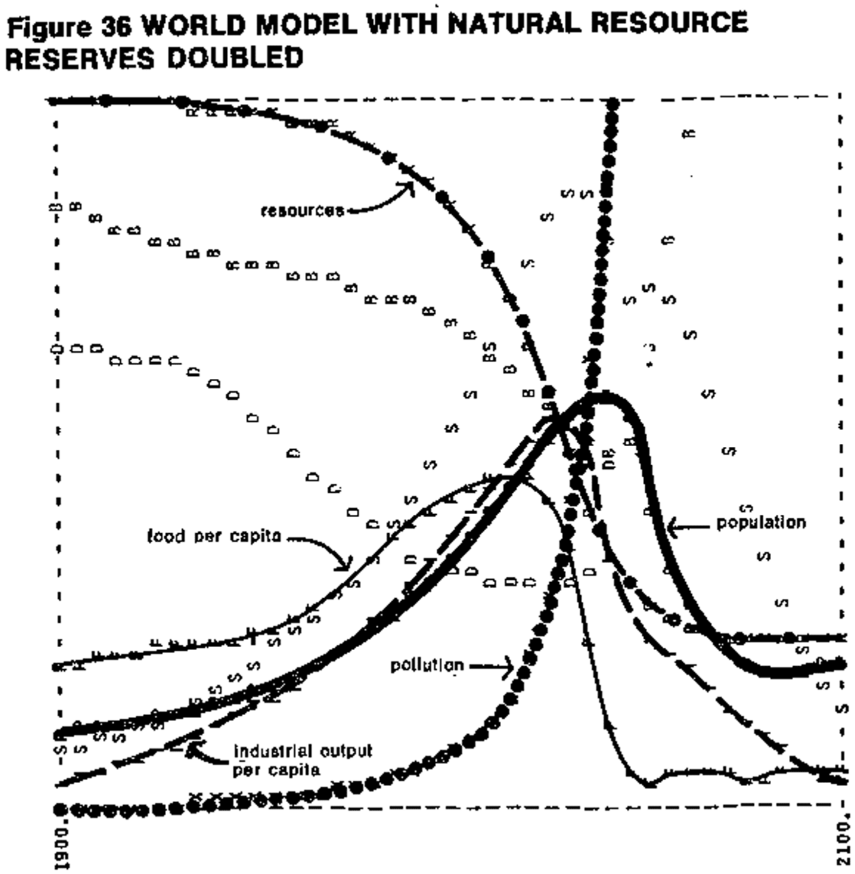

Figure 2. *Scenario n. 2 of The Limits to Growth*[2]*. In this case, natural resources are assumed to be double those estimated in 1972. The population peak occurs at approximately 2050 at a population of approximately 13 billion. Compared with the base case, the collapse occurs earlier and for a larger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

4. A Case Study: Ireland's Great Famine

The case of Ireland's Great Famine provides a good example of how traditional demographic models can miss a rapid population decline. The famine struck Ireland in 1845 as a result of a failure of the potato crops. Several years of poor harvests led to a rapid population collapse caused by hunger, disease, and emigration. The data are shown in Figure 3.

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 answered by developing simple demographic models. The results are shown in Figure 3; the methods are described in detail in the Appendix.

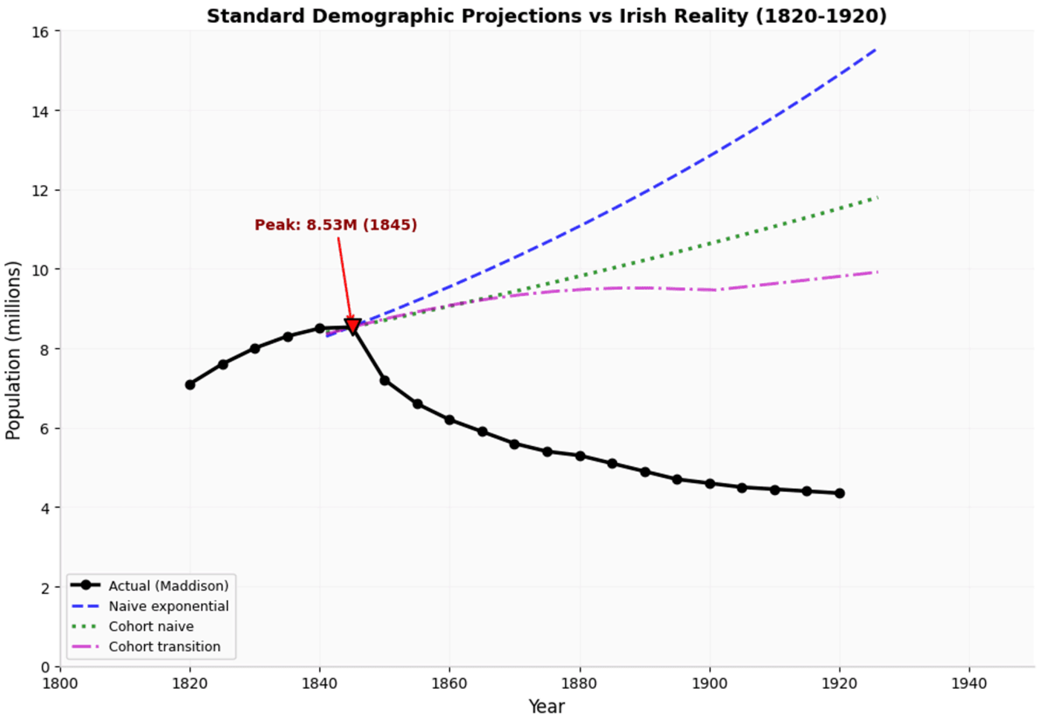

Figure 3. *Standard demographic projection methods applied to Irish population data (1820–1845). The solid black line shows the historical Maddison Project data, revealing the Seneca Effect: rapid population growth to 8.53 million (1845) followed by catastrophic collapse after the Great Famine. Dashed lines show three standard demographic projections — naive exponential, cohort-component (naive), and cohort-component (transition) — all assuming parameter continuity. None could describe the non-linear collapse to 4.35 million by 1913.*

As expected, no simple demographic model could have caught the disaster of 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	13.5 M	+200%
Cohort-Component (Naive)	8.2 M	+82%
Cohort-Component (Transition)	5.7 M	+26%
Actual Historical	4.46 M	—

Table 2. *Demographic projection errors for 19th-century Ireland (1901 projections vs actual).*

A demographer in 1841 using standard methods would have projected 6–8 million by 1901; the actual population was 4.5 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

Standard demographic methods assume parameter continuity — that fertility, mortality, and migration rates evolve gradually along predictable paths. The Irish case demonstrates that structural breaks driven by biological, economic, and social feedback loops can render such projections invalid.

Could a system dynamics model have predicted the Irish population collapse? Plausibly, current models would have proposed a much less optimistic trajectory, but would hardly have been able to capture the brutal decline of the first years after the destruction of the potato crops. Nevertheless, an approach that explicitly models feedback mechanisms (e.g., population pressure → land scarcity → emigration → reduced marriage rates) may better capture such regime transitions than cohort-component methods that extrapolate from historical age-specific rates.

For comparison, a fitting of the Irish historical data was performed using the standard Seneca model[3]. The procedure is described in the Appendix. The model reproduces the historical curve well, but of course, it is based on data that became available only after the famine. A hypothetical system dynamicist 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.

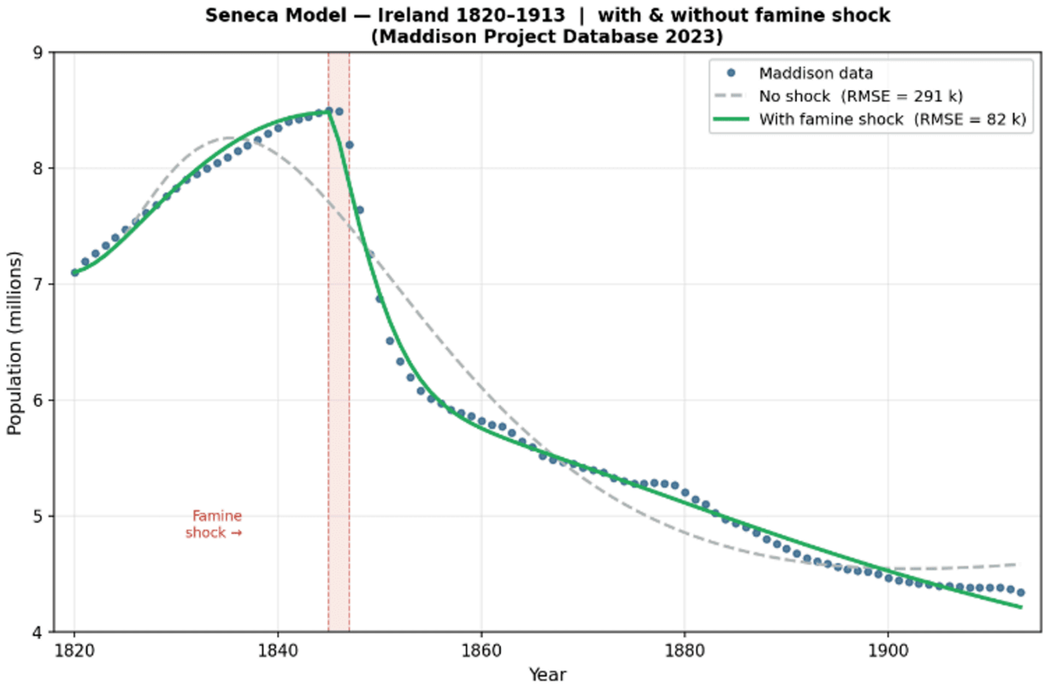

Figure 4. *The Irish population data at the time of the Great Famine fitted with a standard Seneca Model*[3]. *Dots: historical data. Gray dashed line: no famine shock. Green line: famine shock in 1845-46. See the Appendix for details.*

5. Critical Assessment

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 integration	Exogenous scenario	Endogenous feedback

Table 1. 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

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, current policy frameworks assuming gradual demographic transitions may be dangerously complacent. The precautionary principle suggests preparing for more rapid population change than demographic consensus projections indicate, including:

- 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 modeling traditions for human population dynamics generate systematically different predictions due to fundamentally 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.

The consistent pattern across four decades of system dynamics research — earlier peaks (2030–2060), lower peak magnitudes (typically 8–10 billion, although larger in 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 standard demographic models, by their structural design, cannot capture.

Notes

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Appendix: Ireland Case Study

Data Sources

Historical population data for Ireland (1700–2021) were compiled from census records and the Maddison Project Database. The 1841 baseline population structure (8.18 million) was reconstructed using age distributions typical of high-fertility pre-industrial European populations.

1. Naive Exponential Model

Simple curve-fitting using an exponential function $P(t) = P_0 e^{rt}$ with $r = 0.0099$ obtained by fitting the 1700–1841 data.

2. Cohort Demographic Model

The cohort-component method is the standard demographic projection approach used by the UN and national statistical offices. It disaggregates the population into age–sex cohorts and projects each forward using age-specific fertility, mortality, and migration rates.

Step 1: Cohort Survival Projection

The population is divided into n five-year age groups: 0–4, 5–9, 10–14,..., 80–84, 85+. Let $P(a,)$ denote the population in age group a at time t, where a represents the lower bound of each age group (a = 0, 5, 10,..., 80, 85).

Procedure:

- Initialize: For baseline year t_0, populate the age vector from census data.
- Apply survival rates for each age group a > 0: $P(a, t+5) = P(a-5, t) \cdot s(a-5)$, where s(a-5) is the 5-year survival probability from age group a-5 to age group a.
- Handle the terminal (85+) age group: $P(85+, t+5) = P(80–84, t) \cdot s(80–84) + P(85+, t) \cdot s(85+)$
- The youngest age group (0–4) receives births plus net migration: $P(0–4, t+5) = B(t) + M(0–4, t)$
- Iterate: Set t ← t+5 and repeat.

Step 2: Births Calculation

Total births during the 5-year interval: B(t) = $\Sigma a P_{female}(a,t) \cdot f(a) \cdot 5$, where $P_{female}(a,t)$ is the female population in reproductive age group a and $f(a)$ is the age-specific fertility rate. The summation runs over reproductive age groups: a = 15, 20, 25,..., 45.

The "Naive" Model

The naive cohort-component model assumes all demographic parameters remain constant at their baseline (1841) values: ASFRs f(a) fixed at 1841 levels (TFR = 5.65); survival rates s(a) fixed at 1841 levels (life expectancy ~38 years); net migration rates fixed at pre-famine levels (-20 per 1000). This mechanical extrapolation assumes the demographic regime does not change in response to economic, social, or biological shocks — an assumption violated catastrophically by the Irish case.

3. Demographic Transition Scenario

The demographic transition model assumes that fertility and mortality follow the historical pattern observed in industrializing societies: a gradual decline from high pre-industrial levels to low modern levels. Unlike the naive model, it allows parameters to change over time.

Assumptions:

- Fertility decline: TFR decreases linearly from baseline (5.65 in 1841) to replacement level (2.1) over 55 years (1845–1900), then remains constant.
- Mortality improvement: Life expectancy increases gradually from 38 years (1841) to 50 years by 1900.
- Migration: Net emigration increases during the famine period (–50 per 1000 for 1845–1855), then stabilizes at sustained high levels (–30 per 1000).

TFR declines as: TFR(t) = $max(5.65 - 0.064 \cdot (t - 1845), .1)$. The max function ensures that the TFR never goes below the replacement rate. In practice, the historical TFR of Ireland remained above 3.0 until the 1960s, but that was a result of the population "rebound" after the Great Famine, and it is reasonable that it would have declined faster if, hypothetically, the famine had not occurred.

Even this "sophisticated" model fails to capture the Irish reality because:

- It assumes gradual, linear change rather than abrupt regime shifts
- It underestimates the speed and magnitude of fertility collapse (the "Irish marriage pattern" of late marriage and high celibacy reduced TFR faster than standard transition theory predicts)
- It cannot model feedback mechanisms (famine → land consolidation → delayed marriage → lower fertility → more emigration)
- It assumes recovery to equilibrium, whereas Ireland experienced 120 years of sustained decline

The Seneca Model Applied to 19th-Century Irish Population Dynamics Model formulation

The "Seneca Curve" — characterized by slow growth followed by rapid collapse — was modeled using a minimal three-variable dynamical system coupling a renewable resource stock R, a population N, and a cumulative stress (or pollution) stock W[3]:

$$dR/dt = r\,R\,(1 - R/K) - \alpha\,R\,N$$

$$dN/dt = \beta\,R\,N - \gamma\,N - \delta\,N\,W$$

$$dW/dt = \varepsilon\,N - \zeta\,W$$

The resource R grows logistically toward carrying capacity K and is depleted by the population at rate α. The population grows in proportion to available resources (β), decays naturally (γ), and is additionally suppressed by the accumulated stress stock (δNW). The stress stock is generated by population activity (εN) and decays at rate ζ. The asymmetry producing the Seneca shape arises from the delayed accumulation of W: during the growth phase W is low; at the population peak W continues to rise; during decline W is at its maximum, accelerating collapse beyond what resource depletion alone would produce.

Data

Population data for Ireland (entire island) were taken from the Maddison Project Database 2023[13], providing annual estimates in thousands of inhabitants for the period 1820–1913. The series peaks at approximately 8,497 thousand in 1845, collapses to 6,514 thousand by 1851 in consequence of the Great Famine, and continues a slow monotone decline to 4,346 thousand by 1913 — a textbook Seneca trajectory spanning 93 years.

Fitting procedure

Of the three state variables, R and W are unobservable; only $N(t)$ is matched to data. Population was normalized to the historical peak (N_scale = 8.5 million) and time was measured in years from 1820. The carrying capacity was fixed at $K = 1$. The nine free parameters ($r, \alpha, \beta, \gamma, \delta, \varepsilon, \zeta, R_0, W_0$) were estimated by minimizing the sum of squared residuals between the simulated N(t) and the observed annual series, using a multi-start Nelder–Mead algorithm with the adaptive variant. The ODE system was integrated with the LSODA solver (automatic stiffness detection), with relative and absolute tolerances of 10^{-6} and 10^{-8} respectively.

Exogenous famine shock

A key limitation of the smooth deterministic model is its inability to reproduce the abrupt three-year collapse of 1845–1847 from internal dynamics alone. To represent the potato blight as an external forcing, an exogenous shock was introduced by reducing the effective carrying capacity to $K_{eff} = 0.10$ during the interval $t \in [25, 27]$ (calendar years 1845–1847), then restoring it to $K = 1$ thereafter. The ODE system was integrated in three consecutive segments — pre-shock, shock, and recovery — with continuity of state variables enforced at the boundaries.

Results

Without the famine shock, the best-fit model achieves an RMSE of 291 thousand (3.4% of peak), but reproduces the long pre- and post-famine trends reasonably well. The addition of the exogenous shock reduces the RMSE to 82 thousand (0.96% of peak), with a marked improvement in the collapse phase. The best-fit parameters for the shocked model are: $r = 0.348$, $\alpha \approx 0$, $\beta = 0.057$, $\gamma = 0.037$, $\delta = 0.016$, $\varepsilon = 0.069$, $\zeta = 0.025$, $R_0 = 0.705$, $W_0 = 0.004$.

The near-vanishing of α is physically interpretable: Ireland's agricultural land was not degraded by the pre-famine population, so resource depletion by N was not the proximate driver of collapse. Instead, the W stock — representing accumulated social fragility, nutritional vulnerability, and, after 1847, self-sustaining emigration networks — rises continuously throughout the period and remains elevated long after the famine ends, sustaining the post-famine decline through 1913 even as the resource recovers to full capacity. The model thus captures, in qualitative terms, the historically documented mechanism: the blight was an external shock, but the prolonged depopulation was a structural consequence of the social system's response to it.

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