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Research Article

Can Population Decline Solve the Climate Change Problem? A Mind-Sized Analysis

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Ugo Bardi^{1,2}

1. The Club of Rome, Switzerland; 2. Consorzio Interuniversitario di Scienza e Tecnologia dei Materiali (INSTM), Italy

In this paper, I focus on the question of how a “mind-sized” system dynamics model can help people and decision makers understand the role of human population growth or decline in terms of anthropogenic climate change. Within this simplified model, a reduction in fertility alters the trajectory of the accumulated pollution stock only if it starts early, while the resource base is still abundant; when it starts after resources are largely depleted, it has little or no effect on pollution. These results illustrate the importance of feedback structure and intervention timing; they are not quantitative estimates of the effects of present-day fertility policies. They suggest that mitigating global warming cannot be achieved by simple, solve-all solutions, such as birth control, but requires a structured approach to reduce emissions and the human impact on the ecosystem.

Corresponding author: Ugo Bardi, ugo.bardi@gmail.com

1. Introduction: On Models and Reality

In the 1950s and 1960s, digital computers transformed scientific modeling, enabling far more complex representations of reality than pen-and-paper mathematics could support. Complex systems, such as the prototypical Lotka-Volterra one^[1], could now be examined by following their evolution step-by-step, exploiting the brute power of the machine. However, this power came with a well-known pitfall: the expectation that models should *predict* the future of complex systems with at least some accuracy.

This expectation is a legacy from the triumphs of calculus — the mathematics that lets us calculate a cannonball’s trajectory. But complex, non-linear systems do not behave like cannonballs: ecosystems, populations, financial markets, and weather are examples of systems that routinely confound even sophisticated models. It is not that these systems cannot be simulated, but the model evolution strongly depends on the initial assumptions. The result is that the model and the real system rapidly diverge because of the unavoidable uncertainties in the initial values of the model’s parameters. That’s a limitation sometimes expressed with the well-known sentence: “all models are wrong.” But the sentence should be accompanied by the corollary, “all models are useful if you understand their limitations.” Models of complex systems are useful not because they can tell us what the future *will* be, but what it *could* be.

A correct interpretation of modeling non-linear systems was recognized in the 1960s–70s in two parallel fields, both in large part developed at MIT. There, Seymour Papert developed the concept of “mind-sized” models in his book *Mindstorms*^[2]. His idea was that people learn by constructing “objects-to-think-with” and the “Logo turtle” let children make abstract mathematical thinking concrete and manipulable. At the same time, Jay Forrester was developing system dynamics (SD)^[3], a visual language of stocks, flows, and feedback loops for modeling complex systems, embodied in simple educational tools like the “beer game”^[4] and “bathtub dynamics”^[5]. Both approaches rejected piling up parameters in a black-box computation approach in favor of transparent, “mind-sized” models that non-specialists could build, break, and rebuild. Bardi, Lavacchi, and Perissi later applied this same mind-sized approach to natural-resource exploitation models^{[6][7]}, including games describing oil production and whaling^{[8][9]}.

In the present paper, I am using the mind-sized approach to evaluate a crucial problem for the future of humankind. How do population growth and atmospheric perturbation by greenhouse gases

interact to affect global warming and other forms of damage to the ecosystem (e.g., ocean acidification)? It is a typical example of a complex problem that cannot be approached by simple solutions generated by linear thinking.

The human population has been rapidly growing during the past few centuries but, today, it is slowing down as a result of declining fertility, a phenomenon often termed the “demographic transition” ^{[10][11]}. Most industrialized countries today show a total fertility rate, TFR (children per woman), well under the replacement rate of about 2.1. Many of these countries show a declining native population, partly compensated by immigration. Non-industrialized countries, instead, often show a TFR above the replacement rate. Even in those cases, though, the trend is toward a natality decline. Moreover, for a country with a high infant mortality rate, the replacement threshold is not 2.1, but it is closer to 2.2 ^[12]. Taking this correction into account, it is possible that the average global fertility rate is already below the replacement threshold, although estimates differ depending on the sources and methods used ^{[12][13]}.

These considerations do not imply that the global human population is declining right now, but that a future decline is built into the current population structure and will start playing out in the coming decades. Projections based on system dynamics models find that the population will peak and decline typically before mid-century ^[10], although the UN projections show a later peak, around the end of the 21st century ^[13]. The discrepancy between these two estimates is due to different modeling methods, as discussed in a recent paper by the author ^[14]. In any case, there is general agreement in the field of demography that the human population is going to start declining at some point in the future.

Clearly, a declining human population implies a lower rate of resource consumption and a lower emission rate of temperature-forcing gases, mainly CO₂, as well as a lower overall impact on the ecosystem. The question is: assuming a declining population trend that accompanies a lower output of the world’s economy, assuming also no fundamental changes in the economic and technological societal infrastructures, how and how much could that reduce the ongoing disruption of the ecosystem and global warming? Would policies designed to make this decline faster, i.e., birth control, reduce this disruption even more?

In this paper, I discuss the results of published world models based on system dynamics and also develop a simplified version to gain insight into the question. I show that, within this simplified model, the effect of policies aimed at a faster reduction of birth rates depends strongly on their timing, and that such policies, alone, cannot be expected to substantially alter the pollution trajectory once resources are largely depleted. The model is offered as a pedagogical tool for building intuition about feedbacks and delays, not as a climate projection.

2. Population and Pollution in World Models

The backbone of system dynamics world models is the concept of feedback affecting stocks and flows as the main parameters of the system. They tend to see the economic process as the dissipation of the energy potential of a resource (fossil fuels in world models) that is transformed into industrial capital, and eventually into pollution, then dissipated as low-temperature heat into the environment.

SD world models normally include population as one of their stocks, assuming that it is linked to the economic process by positive feedbacks, for instance by food availability. It is also negatively affected by pollution generated by the capital stock. These models rarely include detailed climate parameters. Rather, they tend to aggregate the damage to the ecosphere caused by human activity in a stock called “persistent pollution” (or, simply, “pollution”). The term “persistent” indicates that this stock decays slowly, with halving times of the order of decades, as expected to be the case for added CO₂ in the atmosphere. From a modeling viewpoint, global warming acts on the system in the same way as all other forms of pollution. This approach has been used explicitly or implicitly by Turner ^[15], Dixon-Declève et al. ^[16], Herrington ^[17], Nebel et al. ^[18], and others.

The 1972 “Limits to Growth” report ^[19], sponsored by the Club of Rome, was one of the first studies to use system dynamics (SD) to attempt a quantitative description of global population trends that took into account physical, economic, and social constraints in a world model.

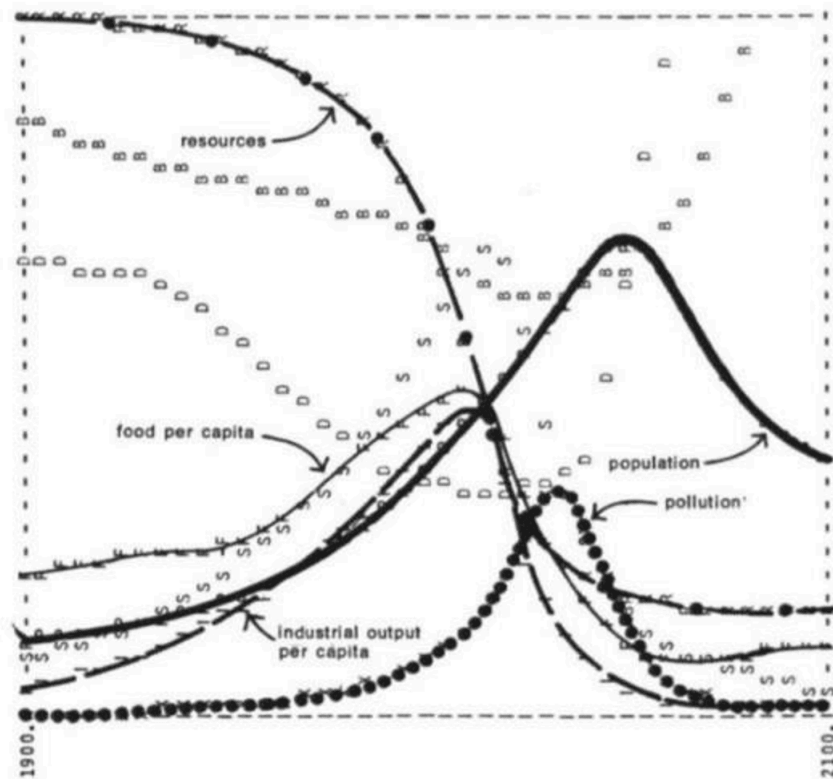


Figure 1. Results of the “standard run” or “base case” run of the 1972 study, “The Limits to Growth,” obtained using the World3 SD model. Image courtesy of Dennis Meadows.

The “base case” or “standard run” scenario was calculated in the 1972 study on the basis of the hypothesis that the main trends of the world’s economy would not change in the future and that the available data set at the time was correct. Up to now, the projections of the model have been found to be reasonably close to the real world’s economic and ecosystemic parameters, although the scenario that assumed larger amounts of available resources produced a better agreement with the historical data. The population was projected to peak and then collapse at some point around the mid-21st century.

The delayed population peak was generated by the assumption that global natality would increase after the economic collapse as a result of a “reverse demographic transition.” That is, fertility would increase despite the plummeting food and service production. This unrealistic assumption was corrected in later versions of the model ^{[20][21]}, which assumed a stronger effect of the declining economy on natality.

Over time, there have been several SD-based reassessments of the world’s population trajectory. In most cases, results similar to those of the first Limits to Growth study were found, but the population peak was generated at an earlier time, and it preceded the pollution peak. As a first example, here are the results of the 2004 sequel to the first Limits to Growth study ^[21]. In this case, the pollution stock peaks shortly after the population peak, around 2030-2040.

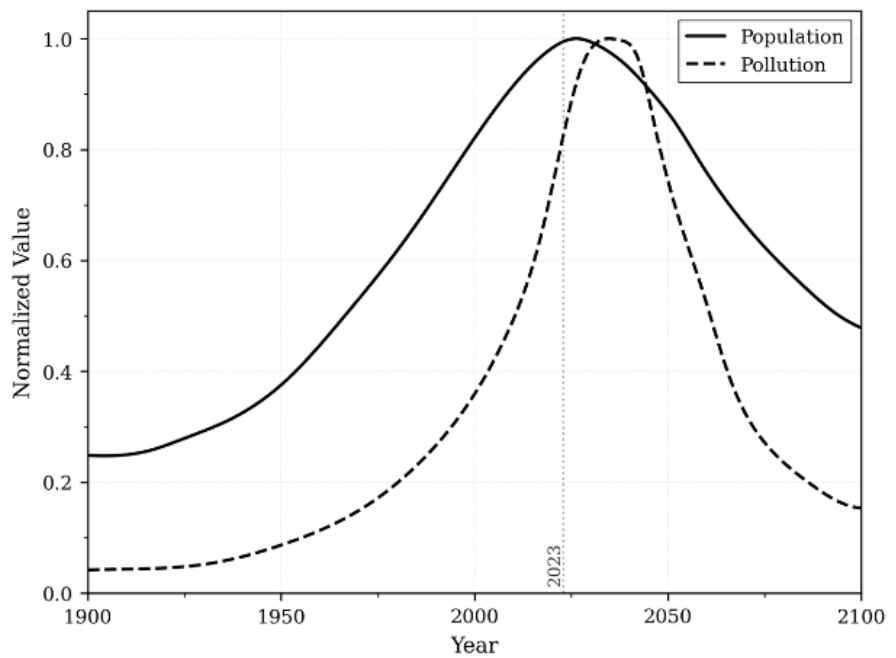


Figure 2. Projections for population and pollution digitized from the “base case” scenario presented in the 2004 sequel to “The Limits to Growth.” [21]

As an example of more recent calculations, here are the population and pollution curves calculated from the results of an update of the World3 model performed in 2024 by Nebel et al. [18]

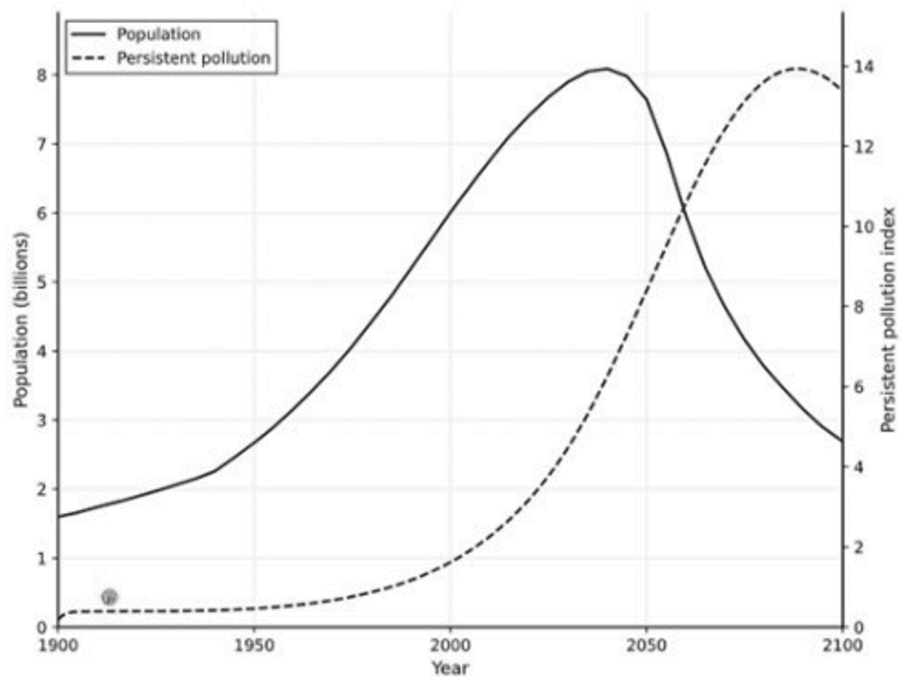


Figure 3. Data for population and pollution extracted from Nebel et al. [18]

The model in Figure 3 shows that the pollution stock peaks at least two decades later than the population stock. Other world-model calculations reported so far generate similar results ^[10].

None of these studies explicitly examined the effect of a birth control effort as a single parameter that reduces natality when the growth cycle of the world's economy was already ongoing. The series of LTG studies (1972 ^[19], 1992 ^[20], and 2004 ^[21]) studied the effect of population control on the world system, but only bundled with several other interventions on the system designed to stabilize both the population and the economy.

3. A mind-sized world model

For the present paper, a system dynamics, 4-stock, mind-sized model was created with the objective of maximum simplification of the system while maintaining the backbone structure of other world models. I assume an economy that grows by exploiting a stock of non-renewable resources – simulating fossil fuel resources. These resources are transformed into economic capital, which decays (depreciates) into the pollution stock. Pollution, in turn, is subjected to a loss proportional to its size (natural reabsorption into the environment). Rather than treating population purely as an outcome of the economy, the exploitation rate (production) is also proportional to a labor factor that increases with, but saturates with, population size. The population stock, in turn, grows proportionally to its size and to that of the economic capital stock. It declines proportionally to its size and to the size of the pollution stock, with an additional crowding term that limits population growth even when pollution remains low.

The pollution-generation term is proportional to the product of the Economy and Pollution stocks (see Supplementary Material, Section S2). This is a deliberately self-catalytic formulation: the larger the accumulated pollution, the larger the fraction of economic capital that must be diverted to coping with it — repairing damage, abating emissions, adapting to degraded conditions — and this diverted capital is itself dissipated into further pollution. In other words, damage accelerates damage. This nonlinear feedback is typical of simplified world models, and it is one of the mechanisms that generate the decline of the Economy stock after its peak. A consequence of this formulation is that the model requires a small, non-zero initial pollution stock, which can be interpreted as the pre-industrial background level of environmental perturbation.

The model structure was drawn in Vensim™ (the causal loop diagram is shown in Figure 4), while the simulations shown in Figures 5 and 6 were performed with a Python implementation of the same equations. The equations, parameter values, initial conditions, and the Python script are provided as Supplementary Material.

4-Stock World Model — Causal Loop Diagram

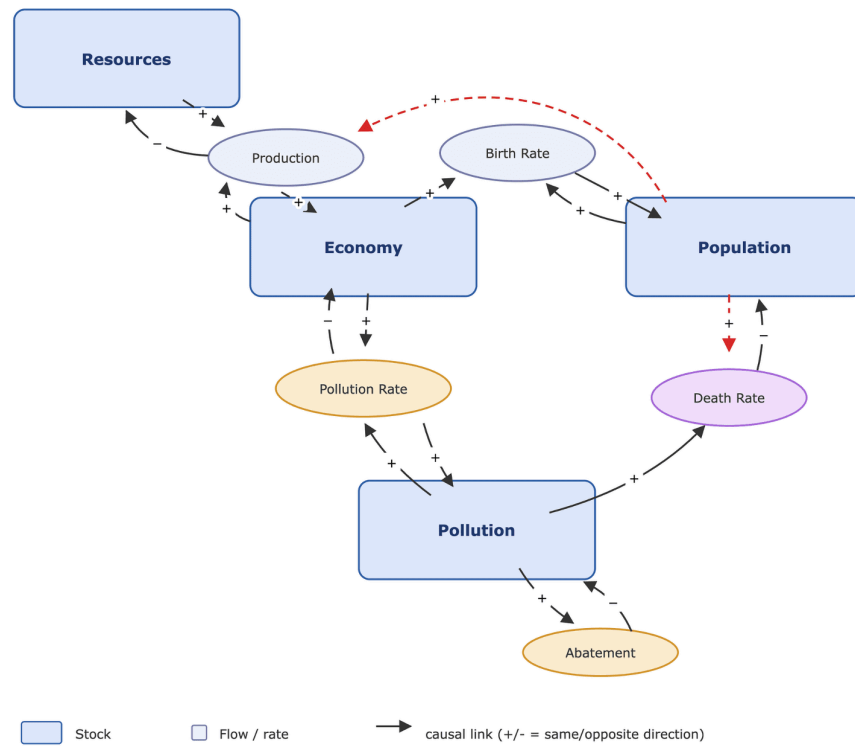


Figure 4. The causal loop diagram for the “mind-sized,” 4-stock world model used in the present study. Dashed red links show the extension introduced here: Population feeding back into Production as a labor input, and into its own Death Rate as a crowding term.

Typical results of the model are shown in Figure 5.

Typical results of the model are shown in Fig. 5.

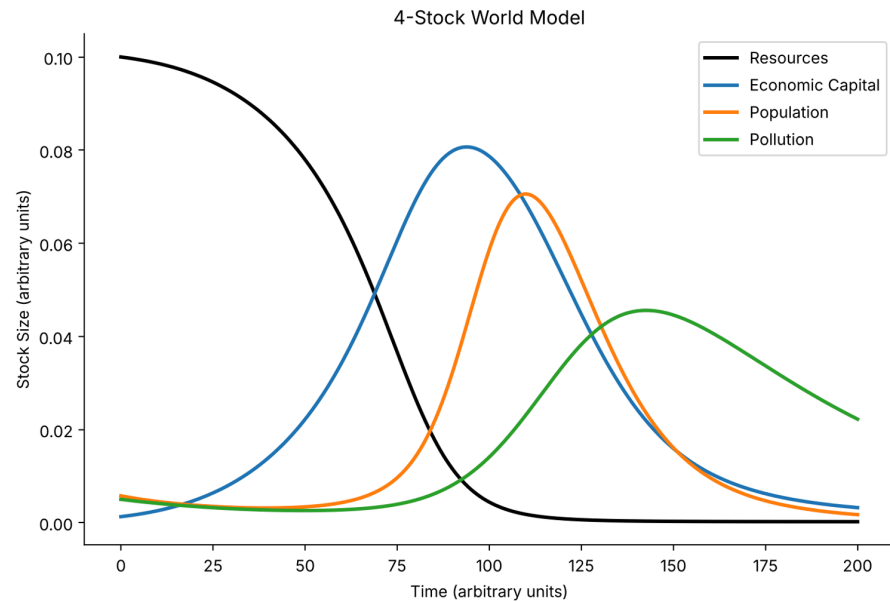


Figure 5. Typical results of the 4-stock mind-sized model – The values of the parameters are in the supplementary material.

The model produces results qualitatively similar to those of more complex world models: a series of sequential bell-shaped curves, growing, peaking, and then declining. The capital stock declines as a result of the combined effect of the increasing cost of the resources and that of fighting pollution. The population stock closely follows the behavior of the economy stock, but its cycle is delayed. The modeled Pollution stock peaks and starts declining significantly later.

The model was tested specifically in view of the effect of birth control, that is, a reduction of the fertility rate not caused by the endogenous interaction but by an exogenous intervention. This exploration was accomplished by varying the birth-rate coefficient (“Kpop”). Since the birth rate is proportional to Kpop ($\text{Birth Rate} = \text{Kpop} \times \text{Economy} \times \text{Population}$; see Supplementary Material, Section S2), a change in Kpop corresponds to a proportional change in fertility, and $\text{Kpop} = 0$ means that no births occur. To examine the role of timing, two interventions — eliminating births ($\text{Kpop} = 0$) and halving fertility ($\text{Kpop} \times 0.5$) — were each started at four different times, $t = 25, 50, 75$, and 100 , and kept in place until the end of the simulation. The results are shown in Figure 6 and Table 1.

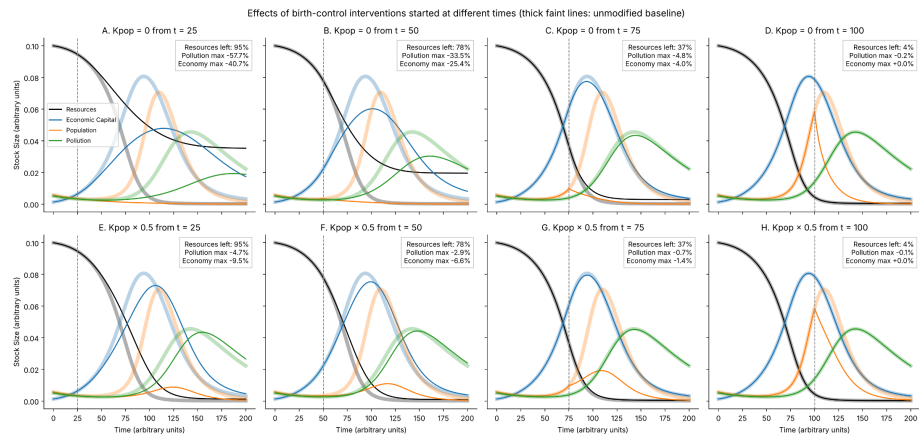


Figure 6. Effect of birth-control interventions started at different times. Thick faint lines show the unmodified baseline; the dashed vertical line marks the start of the intervention. (A–D) K_{pop} set to zero, i.e., no further births, from $t = 25, 50, 75$, and 100 . (E–H) K_{pop} halved from the same times. The boxes give the fraction of the initial Resources stock remaining when the intervention starts, and the percentage change in the maxima of Pollution and Economic Capital within the simulated interval. The effect of the intervention on Pollution depends mainly on its timing. Eliminating births while Resources are still largely unexploited reduces the Pollution maximum substantially (-58% from $t = 25$, -34% from $t = 50$), mainly because the reduced labor force leaves part of the Resources unexploited. Once most Resources have been depleted, the effect becomes negligible (-5% from $t = 75$, -0.2% from $t = 100$). Halving fertility has a small effect at any time (at most -5%), mainly delaying and stretching the Pollution cycle rather than reducing it.

Panel	Intervention (Resources left at start)	Economic Capital peak	Population peak	Pollution maximum ($t \leq 200$)	Pollution at $t = 200$
A	$K_{pop} = 0$ from $t = 25$ (95%)	-40.7%	$-91.9\%^*$	-57.7%	-15.8%
B	$K_{pop} = 0$ from $t = 50$ (78%)	-25.4%	$-91.9\%^*$	-33.5%	0.0%
C	$K_{pop} = 0$ from $t = 75$ (37%)	-4.0%	-86.3%	-4.8%	-0.3%
D	$K_{pop} = 0$ from $t = 100$ (4%)	0.0%	-17.0%	-0.2%	-0.3%
E	$K_{pop} \times 0.5$ from $t = 25$ (95%)	-9.5%	-87.5%	-4.7%	$+19.6\%$
F	$K_{pop} \times 0.5$ from $t = 50$ (78%)	-6.6%	-84.5%	-2.9%	$+8.2\%$
G	$K_{pop} \times 0.5$ from $t = 75$ (37%)	-1.4%	-72.7%	-0.7%	$+0.7\%$
H	$K_{pop} \times 0.5$ from $t = 100$ (4%)	0.0%	-17.0%	-0.1%	-0.1%

Table 1. Effect of birth-control interventions started at different times (changes in the fertility coefficient K_{pop}). Percentage change from the unmodified baseline (Economic Capital peak 0.0807 ; Population peak 0.0706 ; Pollution peak 0.0456 ; Pollution at $t = 200$: 0.0222 , all in arbitrary model units). Peaks and maxima refer to the simulated interval $t = 0-200$. The second column gives the fraction of the initial Resources stock remaining when the intervention starts. Panels correspond to Figure 6. *In panels A and B, Population declines from its initial value and remains low, so that its reported maximum is the initial value.

The results show that the effect of a fertility reduction on pollution depends mainly on when it starts (Figure 6, Table 1). If births are eliminated while the Resources stock is still largely unexploited (panels A and B, with 95% and 78% of the initial Resources remaining), the maximum of the

Pollution stock is substantially reduced, by about 58% and 34%, respectively, and the Economic Capital peak is also lower. This happens mainly because, with a shrinking labor force, part of the Resources is never extracted: about 35% and 20% of the initial stock, respectively, remains unexploited at the end of the simulation. When births are eliminated after most of the Resources have been depleted (panels C and D, with 37% and 4% remaining), the effect on Pollution becomes small (-5%) or negligible (-0.2%), although the effect on Population remains large. Halving fertility (panels E-H) has a much smaller effect at any time: the Pollution maximum is reduced by 5% at most, and the main effect of early interventions is to delay and stretch the pollution cycle, so that pollution at the end of the simulated interval is higher than in the baseline (+20% when the intervention starts at $t = 25$). Early interventions can, therefore, substantially alter the simulated pollution trajectory, but only if they are drastic, and their effects are not uniformly beneficial.

The lesson is one of timing rather than magnitude: within this model, population size acts as a lever on pollution only during the early phase in which economic capital is still being built up from an abundant resource base. These results depend on the assumed resource-depletion trajectory and on parameter values chosen to reproduce a qualitative behavior; they have not been shown to hold for all alternative parameter choices. Time in the model is measured in arbitrary units, and $t = 100$ is not calibrated to any calendar date: it is used here only as an illustrative analogy for a world in which the growth phase of the economy is well advanced. The simulations, therefore, illustrate the importance of feedback structure and intervention timing, but they should not be interpreted as quantitative estimates of the effects of present-day fertility policies.

4. Discussion

The results presented here are illustrations of the general behavior of multi-stock system dynamics models that can approximately describe the trajectory of the real-world economic system coupled with the ecosystem.

The world models discussed in Section 2 share a common qualitative feature: the pollution stock peaks well after the population and the economy (Figures 1-3). Although the pollution stocks represented in these models cannot be directly interpreted as atmospheric CO₂ concentrations without additional calibration, their trajectories illustrate an important feature of stock-and-flow systems, consistent with the long persistence of added CO₂ in the atmosphere [22]: accumulated environmental pressures may continue increasing after the activities generating them have begun to decline. These results should therefore be interpreted as qualitative illustrations of delayed system responses rather than quantitative projections of atmospheric CO₂ concentrations or global temperature.

The models discussed here differ considerably in their assumptions, scaling, calibration, and treatment of pollution, and it is impossible to produce even an estimate of the uncertainty involved. Predicting the future, as mentioned earlier, is difficult, and it becomes more difficult as the time range increases: even the IPCC estimates suffer from a large spread in the estimates, despite being based on sophisticated climate models. In addition, a further element of uncertainty from a dynamical-systems perspective is the possibility of bifurcations, tipping points, and basins of attraction. The non-linear structure of the world's ecosystem could generate more abrupt or irregular transitions than the curves presented here. Exploring that possibility within a comparably "mind-sized" framework is a possibility for future work, but prediction remains fundamentally impossible.

As mentioned before, the point of this paper is not to provide a further uncertain estimate of the future planetary temperature. It is to examine how population decline can affect the accumulation of persistent pollution, of which atmospheric CO₂ is the most important example, and, hence, warming. Would making the decline faster by birth control help reduce future global warming? Within the present model, the answer depends on timing: once the growth phase of the economy is well advanced, a faster population decline has little or no effect on the accumulated pollution.

The simplified world model developed here indicates that, once the resource base is substantially depleted, even a drastic fertility decline has little or no effect on the trajectory of the "Pollution" stock. To the extent that the present state of the world is qualitatively comparable to that phase, birth control cannot be expected to make a large difference to the progression of global warming. This result is in good agreement with the interpretation provided by Spears and Geruso in their recent book *After the Spike* [23], even though their result is obtained within the framework of different, non-dynamic models.

In short, global warming is not a problem that can be solved with a single solution. Reducing the human impact on the planet cannot be done by birth control alone. It takes an integrated approach

based on replacing fossil fuels with renewable energy as a promising, non-traumatic way to mitigate global warming. Calculations performed some years ago that take into account these factors indicate that such a strategy could still be possible, although the window of opportunity may be closing [24]. Exploring this road by means of mind-sized models is a possible future line of research.

5. Conclusion: The Debate on Mitigation

Modeling is a two-edged sword. It can lead us to useful insight on the future, but, at the same time, it may delude us with its pretense to be able to predict the future. We saw in the present paper how models based on system dynamics provide consistent results on the interaction of population decline and global warming trends. These are not predictions: the models provide us with a better understanding of the system.

The purpose of this discussion is to provide a basis for the current effort on global warming mitigation. The mainstream approach assumes that the population trajectory is an exogenous parameter in the models, not to be changed by policy changes [10]. An opposite viewpoint has been commonly discussed in the past, and it is now re-emerging in the discussion [25]. It assumes that population is the central issue and calls for a rapid reduction obtained by policies aimed at reducing natality. As is normally the case, extreme views carry an unacceptable, and often dangerous, simplification of the system being examined. Here, both ways to approach global warming mitigation suffer from substantial shortcomings.

The idea that nothing needs to be done, that the system will evolve by itself into a sustainable situation while population stabilizes, neglects the system's inertia. Even though population and industrial production may slow down their growth, that's not sufficient to stop the concentration of CO₂ in the atmosphere from reaching levels sufficient to cause a catastrophic temperature increase. But even the apparently proactive approach, actively reducing natality, is not sufficient to substantially alter the pollution trajectory within the simplified model discussed here, where a fertility reduction started at an advanced stage of the economic cycle leaves the accumulated pollution practically unchanged. At the same time, a very low natality rate will unbalance the population structure, with a large number of elderly people. So, we need an integrated approach that mixes mitigation with adaptation and recognizes that there are no simple solutions to complex problems.

Statements and Declarations

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Potential Competing Interests

No potential competing interests to declare.

Data Availability

The mathematical model, governing equations, parameter values, initial conditions, intervention scenarios, and associated simulation results supporting this study are documented in the Supplementary Material accompanying this article. The executable Python implementation (extended_model_27Oct26.py) is available as an accompanying supplementary file.

Author Contributions

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

Use of Generative AI

The author used generative AI tools, including Anthropic's Claude and Moonshot AI's Kimi, to obtain critical feedback on the manuscript and to assist in writing the Python implementation of the model. The manuscript was written by the author, who retains full responsibility for the accuracy, integrity, originality, and scientific conclusions of the work.

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