ISSN 2075-5457 (print), ISSN 2220-9697 (online)

••• МОДЕЛЮВАННЯ У БІОЛОГІЇ ••• BIOLOGICAL MODELING •••

DOI: https://doi.org/10.26565/2075-5457-2026-46-3
UDC: 314.17:004.94:378.147

From Malthusian trap to demographic transition: educational and research aspects of a university simulation course

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This article describes a simulation model developed through a collaborative effort between Master's students, PhD students, and lecturers within the course "Simulation Modelling of Stability and Evolution of Supraorganismal Biosystems". Over a series of academic sessions in the R environment, the "Humanity Growth" simulation model was developed, which features a step-by-step increase in systemic complexity. This model belongs to the category "mechanism-sufficiency models" (models that test whether a proposed mechanism is sufficient to reproduce observed dynamics). The baseline architecture consists of an exponential population growth model with several age classes, each characterized by its own birth and death rates. In subsequent stages, the model sequentially integrates: a logistic constraint on carrying capacity (Verhulst parameter); the effect of a time lag in the population's response to resource scarcity (Nicholson parameter); a reduction in environmental capacity resulting from overpopulation crises (Easter Island parameter); the expansion of carrying capacity driven by lifestyle-improving cultural evolution (von Foerster parameter); and, finally, the mechanism of demographic transition (Notestein parameter). The paper discusses the model's structure, simulation results, and alternative algorithmic solutions considered during collaborative development. The authors consider this step-by-step modelling approach successful and offer their experience for its further development and application.

Key words: *simulation, humanity population, population dynamics, sustainability, environmental carrying capacity, lag effect, hyperbolic growth, demographic transition, mechanism-sufficiency models*

***Cite this article**: Nesterenko K.O., Holovnia D.O., Kravchenko M.O., Shorokhova E.A., Sydorova M.A., Surma O.S., Shabanov D.A. From Malthusian trap to demographic transition: educational and research aspects of a university simulation course. The Journal of V. N. Karazin Kharkiv National University. Series Biology, 2026, 46, 23–42. https://doi.org/10.26565/2075-5457-2026-46-3*

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Received: 15.01.2026 / Revised: 21.03.2026 / Accepted: 25.04.2026 / Published: 31.05.2026

Introduction

The analysis of biological population growth is a classic problem in mathematical modelling, tracing back to the early 13th-century "Liber Abaci" – the magnum opus of Fibonacci (Leonardo of Pisa). Since the revolutionary work of Thomas Malthus (Malthus, 1798), modelling the growth of human populations and humanity as a whole has acquired profound significance. While the population dynamics of most species are simulated using exponential and logistic models, a major breakthrough of the 20th century was the realisation that humanity grows in a fundamentally different way from other species: hyperbolically (von

Foerster et al., 1960). In light of this, it is natural that this problem is one of the central topics in simulation modelling courses taught at the Faculty of Biology of V. N. Karazin Kharkiv National University (particularly, "Simulation Modelling of Stability and Evolution of Supraorganismal Biosystems").

We are confident in the high potential of using simulation modelling in education (Kravchenko et al., 2024). Engaging students in the independent or collaborative design of models successfully bridges the gap between classroom instruction and authentic empirical research. A significant advantage of simulation models is the possibility of their step-by-step complication: adding new conditions and feedback loops layer by layer. Under controlled conditions, students have the opportunity to develop initially simple and subsequently increasingly complex systems, making their underlying mechanisms perfectly clear. This approach relies on creative activity, which fosters emotional engagement in the process. Collaborative model building also enables a "brainstorming" style of interaction among participants – developing new models is inherently more motivating than merely replicating predefined templates.

In this article, we outline the logic and structure of the "Humanity Growth" model, which was developed through a collaborative effort involving Master's students, PhD students, and lecturers. This model falls into the category of what can be termed "mechanism-sufficiency models" (models that test whether a proposed mechanism is sufficient to reproduce observed dynamics). Such models determine whether a specific set of assumptions and mechanisms is sufficient to explain the emergence of a particular property of interest within the modelled system. According to the classification we employ (Shabanov et al., 2025), Type I models run a single simulation and describe a specific trajectory of the modelled system in phase space. When these dynamics are indeterminate, Type II models become meaningful, establishing the probability distribution of specific outcomes under identical initial conditions. Type III models involve the step-by-step alteration of one or two initial parameters, constructing a probability distribution of outcomes for each variant to determine how the changing parameters affect the process dynamics. Finally, Type IV models evaluate all possible combinations of initial parameters to determine under which conditions a targeted outcome can or cannot be achieved.

In our view, the "Humanity Growth" model we developed helped students master a range of approaches applicable to simulation modelling, while simultaneously carrying distinct research value. An interesting feature that could be applied in other similar contexts is its incremental complication structure. Within a single script written in the R programming language (R Core Team, 2023), a switch allows the user to choose one of five steps of model complexity. At each step, new conditions or feedback loops are introduced. The output of the model (currently implemented only as a Type I model) describes the trajectory of the system and generates a visualised dashboard that compiles the input parameters alongside an integrated representation of the resulting global population dynamics.

Evolution of Paradigms for Describing Human Population Growth

The uniqueness of human population dynamics

The analysis of human demographic development confronts researchers with the challenge of finding a balance between universal biological laws affecting our species and specific non-linear mechanisms of socio-economic progress. The uniqueness of human populations lies in culture, the coordination of collective actions across different parts of the world, and social institutions, all of which enable society to actively transform its own ecological niche (Cohen, 1998). Yet, humanity remains bound by the planet's material constraints: spatial limits, the regenerative capacity of ecosystems, and the temporal lags of biological reproduction. Humanity cannot entirely eliminate ecosystem inertia, which under certain conditions creates risks of deep ecological overshoot (Meadows et al., 2004). However, society radically reshapes these limits, as humanity has now replaced classic external regulators, such as food scarcity or predation, with endogenous social forces (von Foerster et al., 1960). One of the primary differences between humans and other biological species is that our reproductive behaviour and mortality (at least for the vast majority of society) are mediated by technological advancement, the capital intensity of production, and conscious choices regarding family structure (Galor & Weil, 2000).

At the same time, this progress does not mean a complete release from natural limits: empirical data show that economic scaling and population expansion actually intensify modern civilisation's total reliance on ecosystem services and biodiversity conservation (Guo et al., 2010). Furthermore, today human civilisation faces a series of existential threats stemming from a combination of five global and anthropogenic challenges: climate change, resource depletion, environmental degradation, overpopulation, and rising social inequality (Quinlan, 2020).

A historical perspective clearly demonstrates that the carrying capacity of the human environment is a variable rather than a constant. Economic development has continuously transformed rigid natural feedbacks, as technological revolutions allowed population size to expand without an immediate decline in per capita living standards. Moreover, increasing societal density only fostered the spread of innovations, generating a sustained positive feedback loop between population size and knowledge generation (Kremer, 1993). In the final stages of modernisation, this progress leads to a unique phenomenon – the breaking of the direct link between environmental wealth and fertility, triggering a conscious limitation of family size to facilitate education and human capital accumulation (Notestein, 1945; Lee, 2003).

To systematically describe this complex interaction between biological limits and socio-economic breakthroughs, scientific thought has undergone a long evolutionary journey. The unfolding of theoretical approaches occurred through a step-by-step increase in complexity, moving from the depiction of abstract, unconstrained reproduction to non-linear models of the demographic transition. The classical perspective of Thomas Malthus became the first foundational element along this path.

The Malthusian Model of Exponential Growth

From a long-term historical perspective, human population dynamics show a complex and non-linear character. Following the end of the last ice age, the global population stood at only about 2-4 million people. Over the next twelve millennia, humanity achieved remarkable evolutionary success; as a result, the global population reached its first billion by 1800 and crossed the 7-billion mark in November 2011 (Sojecka & Drozd-Rzoska, 2025).

The first systematic attempt to conceptualize, mathematically describe, and predict the economic impact of this massive demographic expansion was proposed by Thomas R. Malthus in his seminal 1798 work, An Essay on the Principle of Population. The core of Malthusian theory rests on a sharp, non-linear gap between human reproductive potential and the physical limits of the planet. Malthus argued that, without restraining factors, human populations tend to grow at a geometric (exponential) rate, doubling every 25 years, while food production can only increase arithmetically (Unat, 2020).

The Malthusian model relies on two fundamental assumptions:

1. Fixed production factors, primarily a limited amount of agricultural land, meaning that per capita food supply tends to decline as the population grows.
2. A direct link between resources and reproduction, where any rise in living standards and material well-being automatically triggers a positive response in population growth rates (Galor & Weil, 2000).

Following this logic, without technological change or land expansion, a population is doomed to fall into a state of harsh, subsistence-level equilibrium. Even if innovations or the settlement of new territories temporarily boost living standards, population growth completely erases this surplus in the long run. The ultimate outcome is a larger but equally impoverished population, balancing on the brink of physical survival (Abramitzky & Braggion, 2003).

In summary, the baseline Malthusian model established the foundational idea that a population's reproductive potential (r) drives exponential growth. However, this growth inevitably collides with the hard limits of Earth's fixed resources, making permanent, infinite expansion biologically and economically impossible (Meadows et al., 2004; Lidicker Jr, 2020). Yet, Malthus's assumption of an instantaneous collision with these limits – without considering the specific parameters of the environment itself – highlighted the need to revise the model's mathematical framework.

The Classic Verhulst Logistic Model

Despite its long historical success in describing the pre-industrial era, the exponential model failed to capture the dynamics of systems approaching physical and resource limits. Malthus's work was extended mathematically by the Belgian mathematician P. F. Verhulst (1838), who explicitly introduced the carrying capacity parameter (K) into population dynamics. Biologically, K represents the maximum population size that a specific environment can sustainably support in the long term.

By replacing the constant Malthusian growth factor with a relative growth rate that declines linearly with population density, Verhulst's equation describes a clear bimodal behaviour (Sojecka & Drozd-Rzoska, 2025). When the population is small compared to the carrying capacity ($N \ll K$), the system behaves like a Malthusian model with near-exponential growth. As density increases and resources are depleted, a negative feedback loop activates. This guides the system toward an S-shaped plateau – a stationary stabilization phase at level of K (Pelagalli et al., 2025).

This classic sigmoidal trajectory is typical for stable systems with renewable resources, where the ecosystem's regeneration rate fully offsets population consumption. However, the nature and duration of this logistic plateau depend heavily on the type of limiting resources. While the stationary phase can last indefinitely in renewable systems, the picture changes completely for isolated systems relying on non-renewable resources. In such scenarios, the stationary phase is extremely brief. It is inevitably followed by a sharp population decline due to complete resource exhaustion (Sojecka & Drozd-Rzoska, 2025).

Thus, the integration of Verhulst's parameter (K) marked a shift from modelling abstract, unlimited growth to describing real ecological boundaries, where carrying capacity acts as a strict brake on reproductive potential. Nevertheless, Verhulst's logistic plateau remained mathematically stable only under the strict assumption that the population responds to resource scarcity instantly – a condition that fundamentally violates the principles of biological inertia.

The Time-Delayed Logistic Model

The classic Verhulst model relies on a strict simplification: it assumes that population regulation through resource deficits or intraspecific competition occurs instantly. Conversely, in real ecosystems there is a time lag – a delay between the moment a population reaches critical density and the moment this directly affects birth or death rates.

G. E. Hutchinson first proposed the mathematical framework for this phenomenon by introducing a discrete time lag τ into the logistic differential equation (Hutchinson, 1948). Similarly, through analysing insect population dynamics, A. Nicholson demonstrated that reproductive lag and resource-consumption inertia inhibit a system's capacity for timely stabilization as it converges upon the carrying capacity threshold K (Nicholson, 1954).

Research in system dynamics and ecology shows that adding even a minor temporal delay changes the model's behaviour completely. Instead of a smooth transition to Verhulst's stable plateau, the system initiates oscillatory behaviours (May, 1976; Turchin, 2013). Depending on the size of the lag and the population's reproductive potential, simulations identify three primary dynamic regimes:

1. Damped oscillations around K.
2. Stable limit cycles characterized by persistent periodic waves.
3. Chaotic fluctuations, where the population plunges into a deep ecological overshoot. This significantly exceeds the ecosystem's capacity and sets the stage for a subsequent demographic crisis (Berryman, 1999).

Consequently, the introduction of a delay parameter transforms the static logistic model into a dynamic, oscillatory system. The population size responds not to the current ecological state of the environment, but to the state of the system several years or decades ago. This provides a more realistic reflection of biological and demographic inertia. This regime of inevitable ecological overshoot and subsequent collapse became key to understanding the decline of real isolated systems, where a delayed population response to resource depletion physically destroys the habitat itself.

Ecological Overshoot and Carrying Capacity Degradation: The Easter Island Framework

Another fundamental limitation of classic approaches is the assumption that environmental parameters are static and unchanging. In real systems, the carrying capacity of an ecological niche (K) is a dynamic variable. If demographic pressure causes a severe overshoot, the underlying resource base undergoes severe degradation. This turns a smooth growth slowdown into a catastrophic systemic collapse (Rees, 2002; Brandt & Merico, 2015).

The fate of Easter Island (Rapa Nui), an isolated piece of land in the Pacific Ocean, serves as the primary historical model for studying these non-linear human-nature interactions on a global scale. Palaeobotanical analyses of palynological profiles from marsh sediments, coupled with radiocarbon dating of charcoal remnants, establish that during the initial settlement by Polynesian colonists circa 450-500 CE according to some estimates, the island was a densely forested ecosystem with a massive subtropical palm forest. Meeting basic food needs was relatively easy, which stimulated rapid demographic growth. Estimates of peak population range from 7,000 to 15,000-20,000 individuals between the 14th and 16th centuries. However, the unregulated exploitation of this open-access renewable resource led to the complete disappearance of palm trees by around 1400 (Brander & Taylor, 1998). One explanation for the subsequent demographic crisis is the ecocide scenario. Deforestation triggered a series of resource crises. This caused a swift demographic crash to approximately 2,000 people by 1722, accompanied by tribal warfare and cannibalism (Diamond, 2005).

System dynamics modelling conducted by J. Brander and S. Taylor (1998) demonstrates that the emergence of this boom-and-bust cycle was a direct consequence of a specific ecological parameter: the extremely low intrinsic regeneration rate of the native palm trees (Brander & Taylor, 1998). The core issue of overshoot is the uncontrolled depletion of common-pool resources for private gain. As the population grows, individual increases in extraction temporarily mask environmental degradation and delay early warning signals of a crisis. Consequently, by the time society finally notices the ecosystem's collapse, the resource base is already destroyed, leaving no time to establish conservation rules (Anderies, 2000).

The Easter Island model demonstrates that ignoring non-linear feedback and leaving renewable resources unregulated under Malthusian pressure leads to the inevitable destruction of carrying capacity (K). This creates cyclical "feast and famine" processes that directly cause severe systemic conflicts.

However, while Rapa Nui's fragile island biosphere was vulnerable to human pressure, global humanity found a way to counter crises by completely restructuring the production system itself.

Endogenous Technological Progress and Population Expansion: The von Foerster Framework

The next step in the evolution of population growth ideas overcomes the strict ecological limits of Malthus and Verhulst by introducing a mechanism of endogenous technological progress. In a society with high levels of communication and information exchange, humanity breaks its linear dependence on natural resources. The anthropogenic habitat becomes increasingly mediated by endogenous technological vectors (von Foerster et al., 1960). This enables the system to actively expand the parameters of its environmental carrying capacity rather than passively adjusting to a static limit.

The fundamental manifestation of this pattern is the hyperbolic growth effect (von Foerster et al., 1960). The authors demonstrated that if the growth dynamics of the past two millennia continued, the accelerating gap between birth and death rates would cause the population curve mathematically to approach infinity on a specific critical date: Friday, November 13, 2026. This anomalous acceleration is the result of the population growth rate becoming proportional not simply to the current population size, but to its square. This relationship reflects intensifying social interactions and bypasses the immediate intervention of exogenous resource scarcity.

Michael Kremer (1993) provided an economic and evolutionary justification for this phenomenon. He built an integrated model linking the Malthusian assumption of resource-limited population to the concept of endogenous innovation. This approach partly echoes Esther Boserup's theory, which argued that demographic pressure forces societies to develop new technologies when the old resource base can no longer sustain them (Boserup, 1965).

Integrating the technological factor into the model shows that a larger population produces more knowledge, which in turn expands carrying capacity and drives further accelerated growth. However, Kremer's model includes an important caveat: as per capita income rises alongside technological progress, it eventually triggers a reverse reaction – a decline in fertility rates at high wealth levels. This shifts the system toward the final demographic transition, ultimately enabling the global system to break the Malthusian trap, shifting from quantitative expansion to internal qualitative stabilization.

The Demographic Transition in a Closed Ecosystem: The Notestein Framework

The final step in system complexity describes a turning point in global societal development. This stage marks the breaking of the centuries-old Malthusian constant and the transition of the eco-economic system into a regime of modern sustainable growth. The mathematical and theoretical foundation of this process rests on the classic demographic transition theory, which was pioneered by W. Thompson (1929) and later fully formalized by F. Notestein (1945).

He was the first to systematically link declining fertility with industrialization. The model of endogenous development reflects this historical evolution of population, technology, and production through three sequential regimes (Galor & Weil, 2000):

1. The Malthusian regime: where short-term income gains are quickly erased by population growth, returning society to the subsistence level.
2. The Post-Malthusian regime: where innovation outpaces resource degradation for the first time, allowing both population and living standards to grow simultaneously.
3. The Modern Growth regime: which marks the final demographic transition.

The main driver of this transition was a shift in parental choice, prioritizing child survival and success over offspring quantity. Rapid technological progress devalued the basic agricultural knowledge of previous generations. This created a high demand for quality education. This triggered a new feedback loop: investments in human capital accelerated innovation, which made education even more valuable and drove down fertility rates. Beginning in Europe around 1800, this global transition radically altered demographic structures. Within the population studied by Lee (2003) birth rates fell, aging intensified, and the share of a woman's adult life spent raising infants dropped from 70% to 14%, freeing up time for other socio-economic activities.

In conclusion, integrating the demographic transition parameter completes the logic of historical development. The system overcomes the threat of a non-linear Malthusian catastrophe or ecological overshoot not through infinite physical expansion, but through an internal, qualitative transformation: human capital accumulation and the endogenous stabilization of population size within the biosphere's carrying capacity.

Materials and Methods

The methodological structure of this study is built on the principle of step-by-step expansion and scaling of simulation models. For ease of reading, the mathematical description and algorithmic schemes for each step of the author's model are presented directly in the "Results and Discussion" section. This allows for a synchronous comparison of specific architectural changes in the model with their corresponding graphs and simulation results.

Simulation modelling serves as the primary research tool, as it enables the analysis of non-linear processes across multi-millennial timescales, which is impossible through direct empirical observation. This work utilises a system dynamics approach rather than agent-based modelling. While the agent-based approach focuses on the discrete actions of individuals and micro-level behavioural rules, system dynamics prioritises aggregated population states (stocks) and macro-level rates of change between them (flows). This approach aligns with the systemic principles outlined by Meadows (2008), according to which the internal structure of a system, defined by a combination of positive and negative feedback loops, time lags, and resource constraints, is the primary determinant of its long-term dynamic behaviour.

Algorithmic execution, progressive model complication, and graphical data visualisation were fully implemented within the R programming environment. The baseline demographic structure relies on dividing the population into age classes (cohorts), each characterised by specific birth and death rates. This matrix serves as the foundation for the subsequent implementation of five consecutive non-linear modifications.

Results and Discussion

General structure of the "Humanity Growth" model

The "*Humanity Growth"* model describes the dynamics of a population consisting of several age classes(***n_classes***), where individuals spend ***age_step*** years per class. In the model program code text provided in Appendix 1, a configuration with 9 age classes of 7 years each is selected, meaning the maximum lifespan is 9×7=63 years. This model focuses only on the female population; the total population size can be assumed to be approximately twice as large. Each class is characterised by ***b[i]*** – fertility, defined as the expected number of newborn females per woman of class i per year and ***d[i]***, representing the annual probability of death for an individual in class ***i***.

At the beginning of the simulation, the initial number of females (N_0) is evenly distributed among all age classes. The number of individuals in the first age class may be smaller to ensure that the total population matches N_0 and each class contains an integer number of individuals.

The conceptual baseline logic of the model is shown in Fig. 1, utilising the notation standard for stock-and-flow diagrams (Meadows, 2008). Step 0 is the conceptual baseline representing exponential growth with age structure; it is not selectable via the step switch but is implicitly contained in all higher steps.

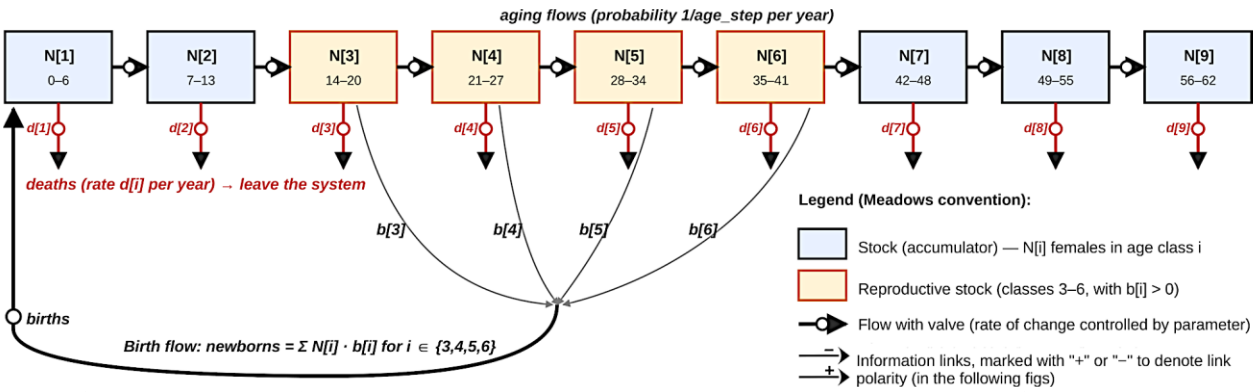

Fig 1. Step 0. A model of exponential population growth that separately accounts for birth and death rates in different age groups. Conventions according to the stock-and-flow diagram (Meadows, 2008). No feedback loops yet:
• ***b[i]*** and ***d[i]*** are constants (do not depend on ***N***);
• Population grows or declines purely exponentially;
• The Malthusian parameter $r \approx b - d$ emerges from the structure.

An important element of the model is the ***step*** switch, which can take integer values from 1 to 5. It determines which set of regulatory assumptions for population dynamics applied during a given simulation run. Each subsequent level incorporates all the mechanisms of the previous level along with a new feature. A specific block of parameters is assigned to each step to govern its unique regulatory pathways.

The script then describes the creation of objects used for calculations and user-defined functions. These include functions for updating the carrying capacity K (for steps 3, 4, and 5), checking for sustained growth and decline of K (for step 5), and the full operating cycle of the model, which conventionally corresponds to one year of the population's life (for all steps).

The main operating loop of the model repeats as many times as specified by the ***cycles*** parameter (the simulation duration in years), unless the simulated population falls to zero. During every iteration, the size of all age classes and the values of other key variables are recorded in the ***Results*** matrix.

The output of each simulation consists of the ***Results*** matrix and a dashboard containing windows that report the conditions of the model experiment, the overall population dynamics throughout the simulation, and age structures at designated time intervals. At step 5, an additional window is added to reflect the dynamics of the demographic transition.

Step 1: Verhulst parameter (environmental carrying capacity)

The first step in constructing the simulation model involves transitioning to a logistic dependence. Fig. 2 indicates the new features implemented during this initial step.

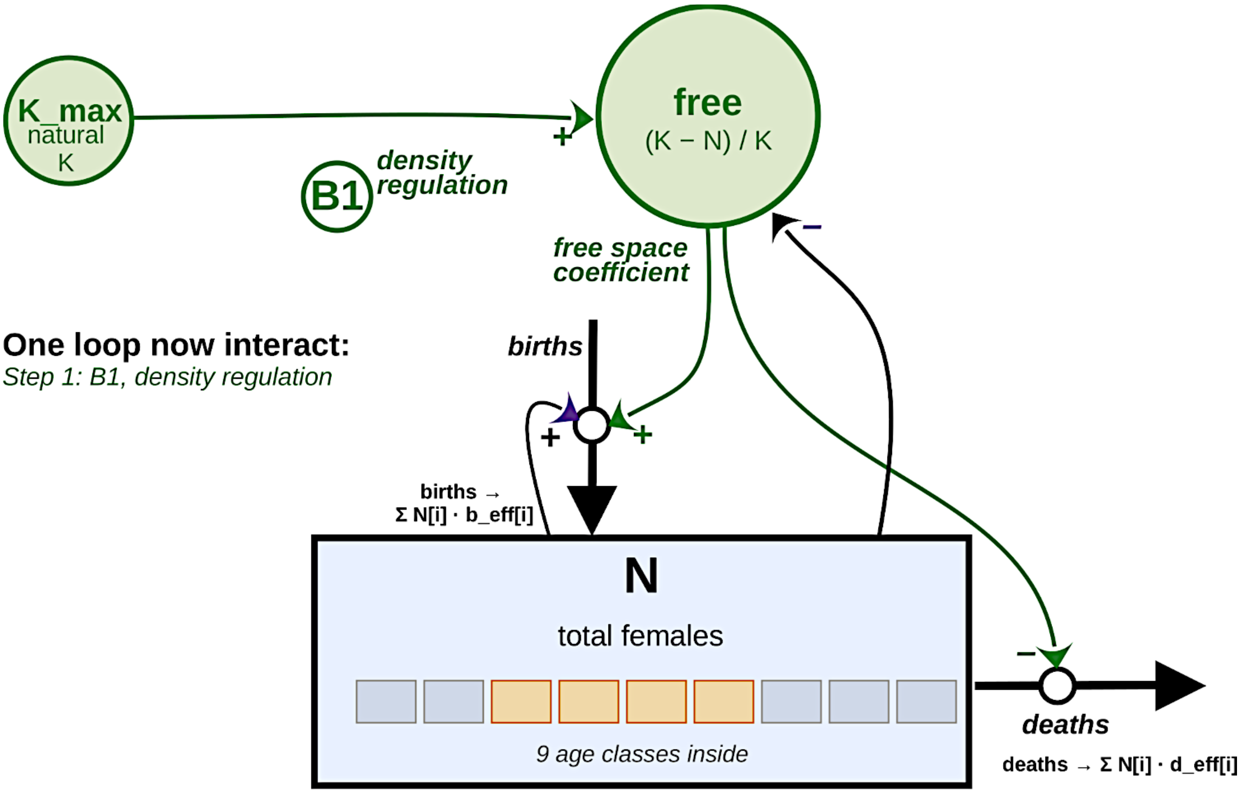

Fig 2. Step 1. Incorporating the effects of environmental carrying capacity (specified by the Verhulst parameter) on birth and death rates. New in Step 1 (vs. Step 0):
• Population ***N*** is now shown as a single aggregated stock (its internal age structure remains as in Step 0);
• New parameter ***K*** (carrying capacity) and auxiliary ***free = (K−N)/K***;
• First feedback loop: as ***N*** grows, free shrinks, which reduces births and increases deaths — population stabilizes near ***K***.

The results of modelling human dynamics for this particular phase are omitted here. The simulated population size stabilises at a level below K_{max}. This outcome occurs because every age class utilizes environmental resources (decreasing the free variable), yet only specific cohorts contribute to reproduction. If the carrying capacity of the environment supports not only fertility but also mortality, the population size will stabilise at a lower threshold.

Fig. 3 displays the modifications introduced in step 2. A delay in the population's response to environmental constraints can lead to an overpopulation crisis and subsequent collapse (Fig. 4).

Step 2: "Nicholson parameter" (delay in the population's response)

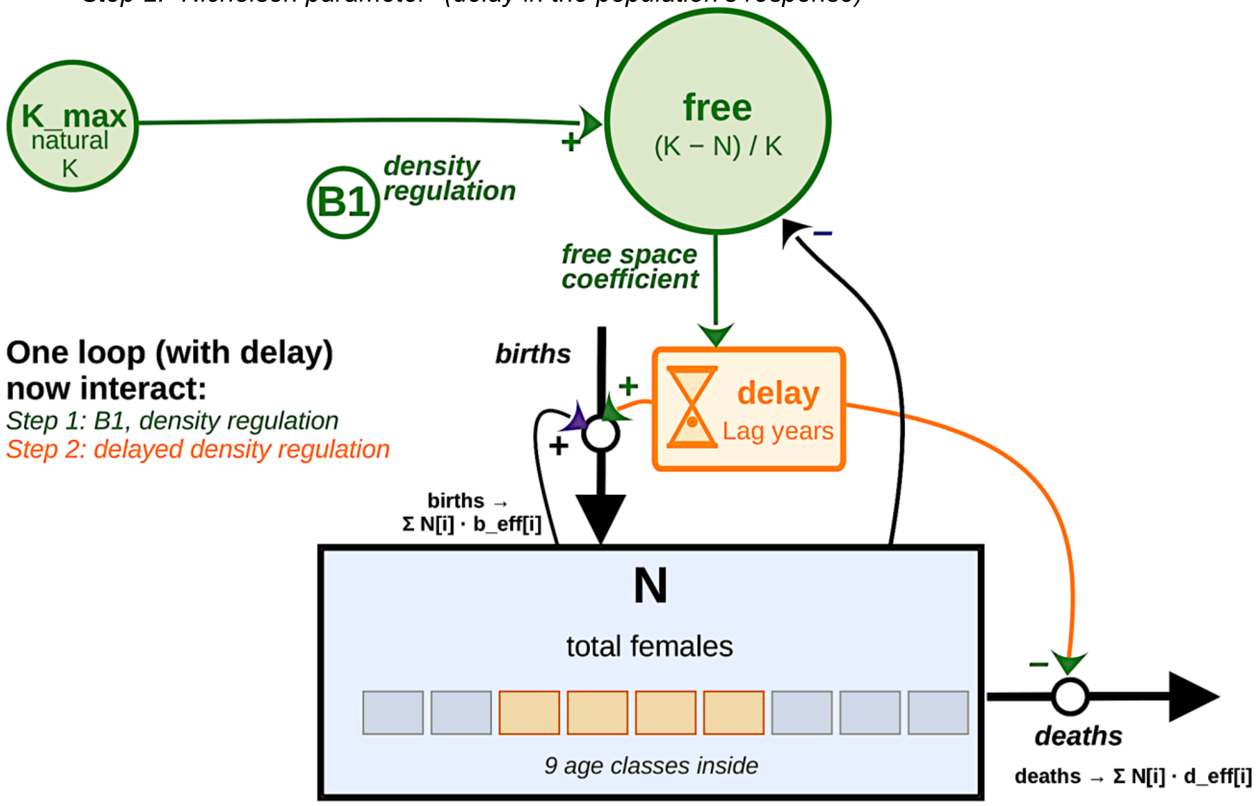

Fig 3. Step 2. Incorporating the delay in the global population's response to environmental capacity constraints (as determined by the "Nicholson parameter"). New in Step 2 (vs. Step 1):
• Environment still reacts to current N instantly: ***free = (K − N) / K*** is computed from the current ***N***;
• But population reacts to environment with a delay (***Lag*** years);
• Today's reproducers were born ***~Lag*** years ago in response to free space available back then.

The construction of Fig. 4 uses a practical opportunity for model experimentation. To evaluate model behaviour under specific input parameters, the ***set.seed()*** function allows users to define the initial state of the pseudorandom number generator. This ensures that the simulated system follows the exact same trajectory during repeated runs. By analysing the Results matrix, which describes this trajectory, it is possible to select specific moments in the history of the global population for closer inspection. These selected moments (which are added to the ***time_points_custom*** vector) are highlighted with coloured markers on the "Population dynamics" chart, and their corresponding age class distribution curves are displayed on the "Age structure" plot.

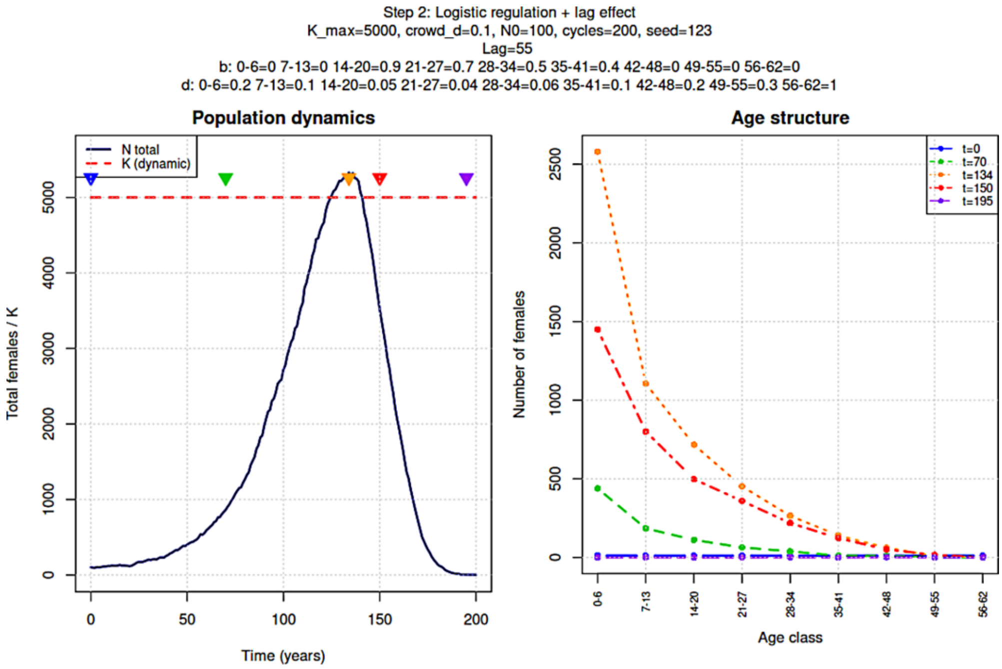

Fig. 4. Temporal delay in the simulated population's reaction to environmental limits (the Lag parameter) leads to its collapse

Even with a shorter response delay, the population can experience sharp fluctuations in size with a randomly varying amplitude. Eventually, this can drive the model population to a complete crash (Fig. 5).

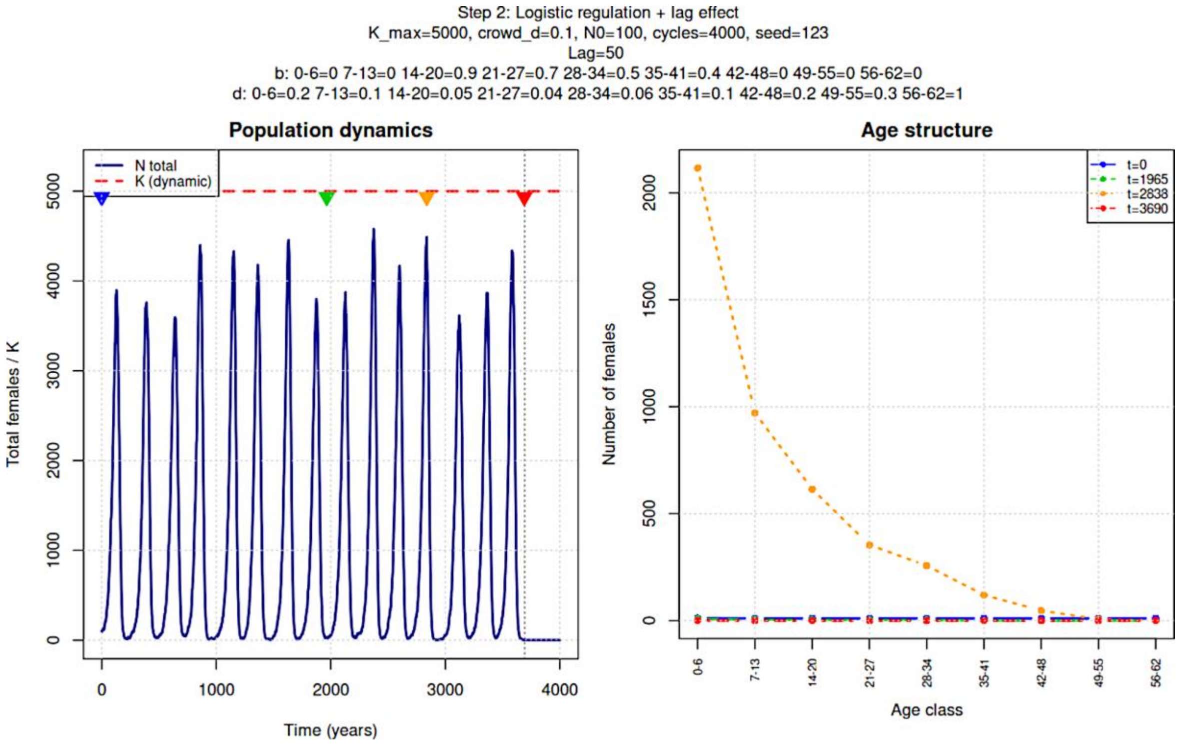

Fig. 5. A delay in the population's response to constraints led to its collapse after a series of oscillations

Step 3: "Easter Island parameter" (environment degrades in the event of an overpopulation crisis)

The next step considers the principle that a population exceeding its carrying capacity causes environmental degradation. Step 3 also takes into account the opposite scenario – the gradual recovery of the environment, if its exploitation is not excessive. However, the typical case is likely one where recovery is a much slower process than the depletion that occurs during a Malthusian crisis. The modifications to the model at this step are illustrated in Fig. 6.

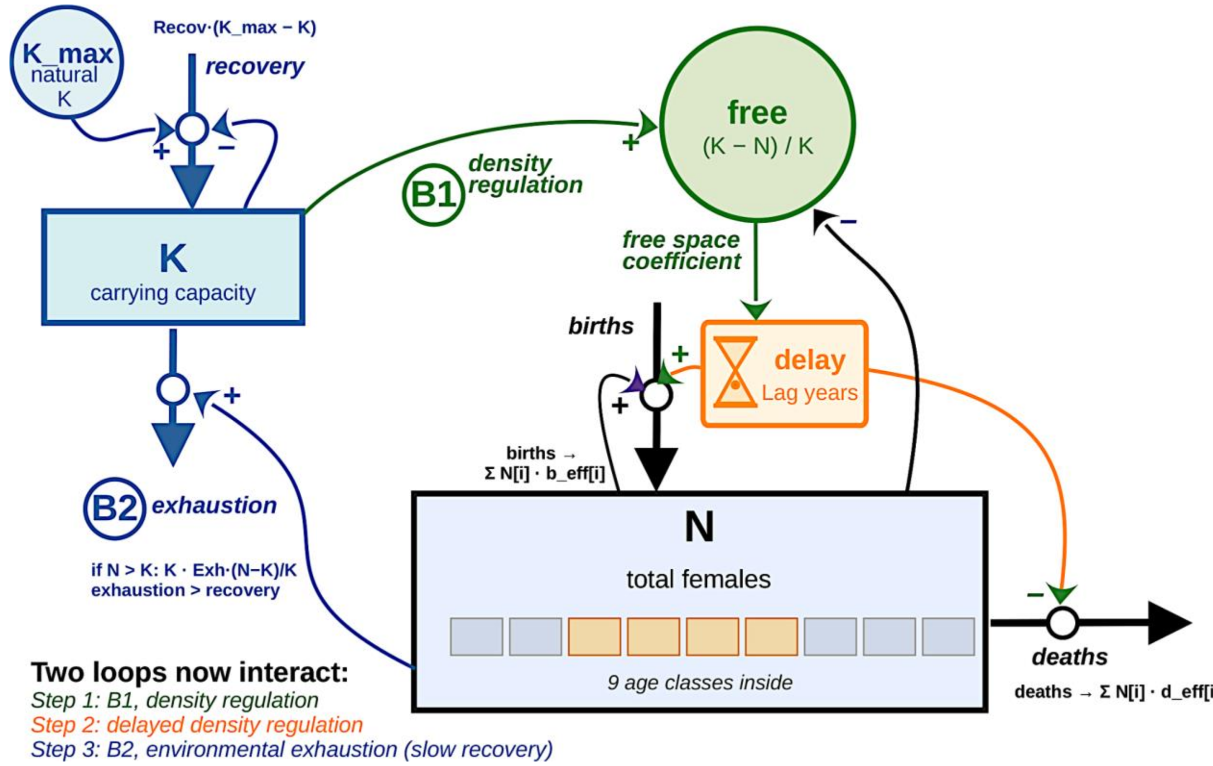

Fig 6. Step 3. Incorporating the environment degrades in the event of an overpopulation crisis (as determined by the "Easter Island parameter"). New in Step 3 (vs. Step 2):
• K is no longer a fixed parameter — it becomes a dynamic stock;
• Two new flows: recovery ***(K_max − K) · Recov*** and exhaustion;
• If ***N*** exceeds ***K***, the environment degrades (Easter Island effect);
• Recovery is slow (***Recov ≪ Exh***): damage outpaces healing.

Under such conditions, even relatively small overpopulation crises can significantly reduce population resilience and cause its collapse (Fig. 7).

 ISSN 2075-5457 (print), ISSN 2220-9697 (online)

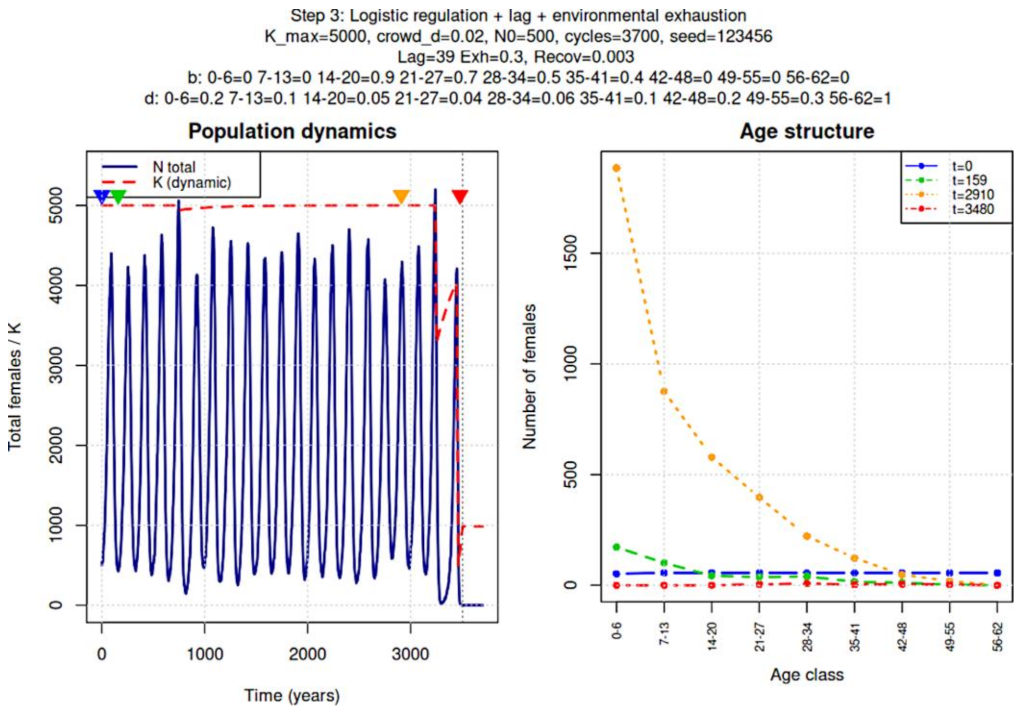

Fig. 7. The population recovered after the first two overpopulation crises but collapsed after the third

Step 4: "von Foerster parameter" (increase in environmental carrying capacity)
The hyperbolic human population growth, discovered by Heinz von Foerster (von Foerster et al., 1960), results from lifestyle changes driven by cultural evolution. Conventionally, the rate of this process can be considered proportional to the population size, as implemented in the fourth step of model complexity (Fig. 8).

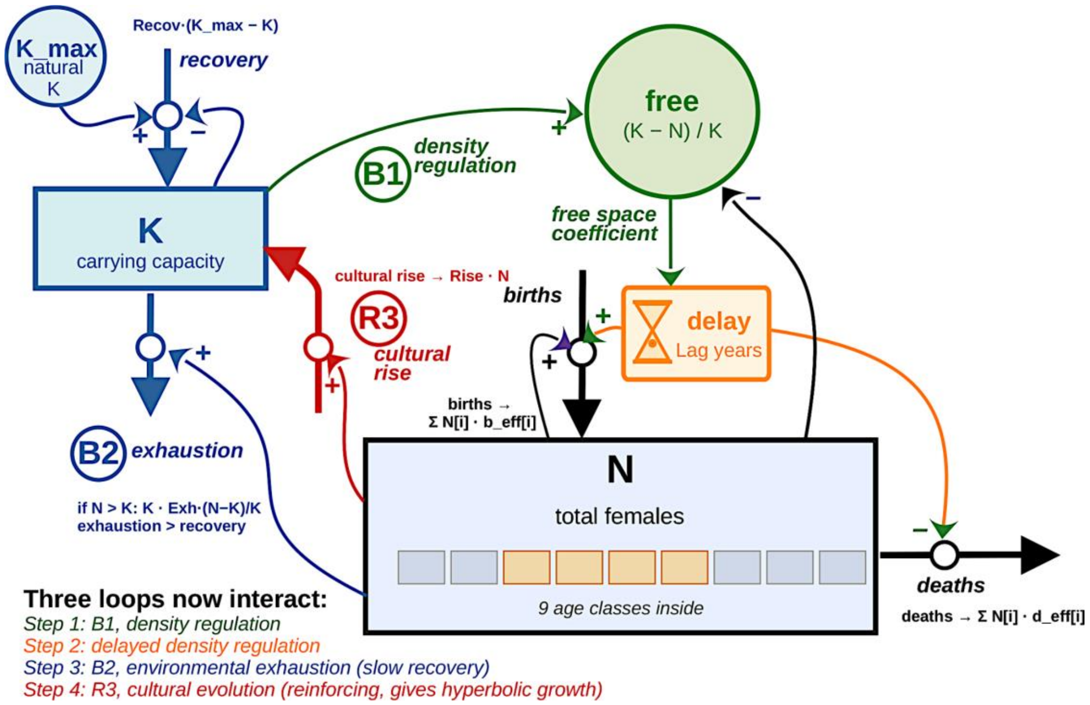

Fig 8. Step 4. Incorporating the increase in environmental carrying capacity resulting from cultural evolution, which optimizes the way of life (as determined by the "von Foerster parameter"). New in Step 4 (vs. Step 3):

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• Population itself enriches ***K*** through cultural evolution;
• Rise flow adds ***Rise · N*** to ***K*** each cycle: more people → more "inventors" → faster cultural growth;
• This generates the first reinforcing (positive) feedback loop;
• Hyperbolic growth of ***N*** becomes possible (von Foerster effect).

As shown in Fig. 9, even with a continuous increase in carrying capacity, a delay in the population's response to constraints can lead to a Malthusian crisis, resource depletion, and population collapse.

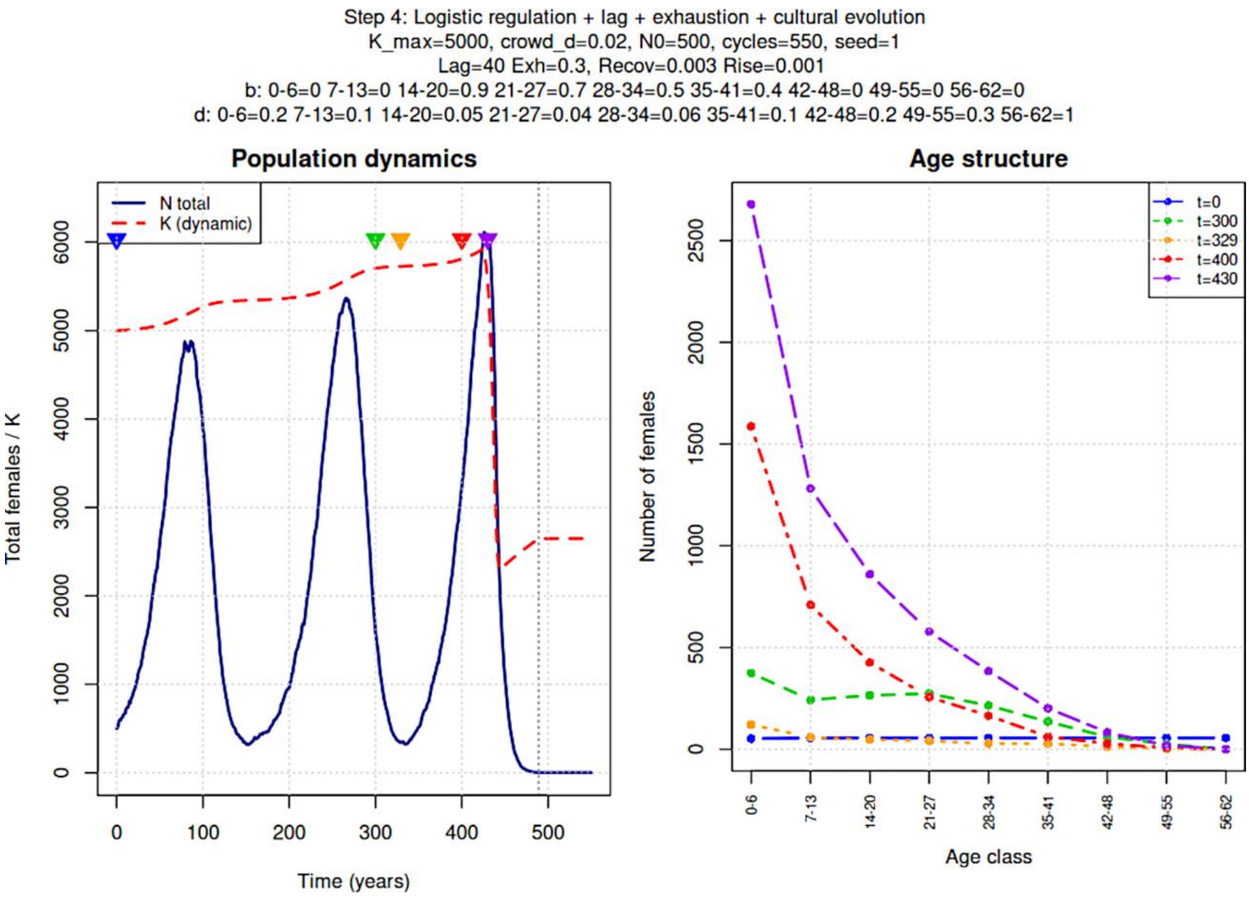

Fig. 9. Even under conditions of growing carrying capacity driven by human cultural evolution, a delay in the global population's response to external constraints can lead to the collapse of the simulated system

Step 5: “Notestein effect” (demographic transition)

The long-term sustainability of the global population depends on the demographic transition, a feature introduced in the fifth stage of refining our "Humanity Growth" model (Fig. 10).

 ISSN 2075-5457 (print), ISSN 2220-9697 (online)

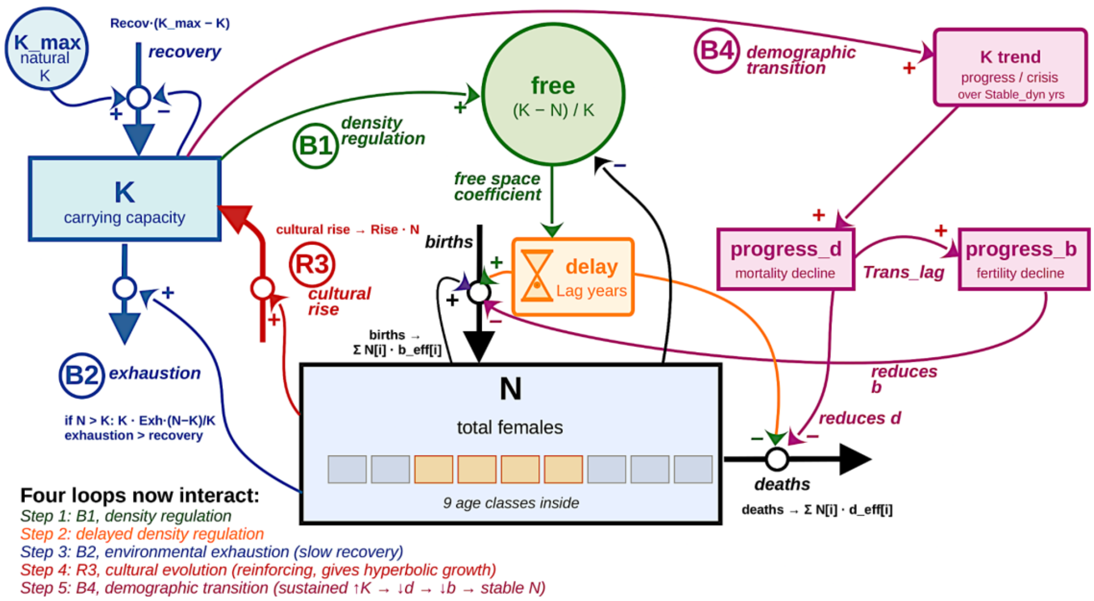

Fig 10. Step 5. Incorporating the demographic transition ("the Notestein effect"): sustained growth in environmental carrying capacity leads to a decline in mortality, followed by a decline in fertility.
New in Step 5 (vs. Step 4):
• Sustained growth of ***K*** (over ***Stable_dyn*** years) triggers social progress: humanity adapts its reproductive behaviour;
• Stage 1: mortality declines (***progress_d*** grows toward 1);
• Stage 2 (after ***Trans_lag***): fertility declines (***progress_b*** grows);
• Reversible only during crisis (sustained ***K*** decline).

During the fifth stage of simulation, the model population is most vulnerable precisely at the onset of the demographic transition, when mortality begins to decline while birth rates remain high.

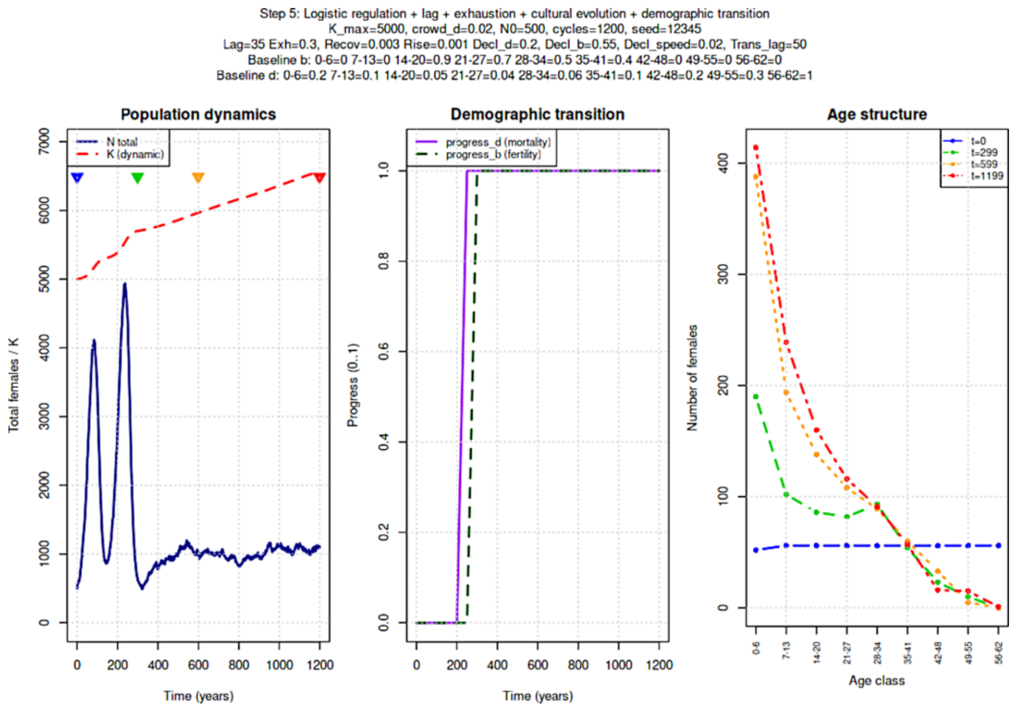

Fig. 11. The result of the demographic transition is the long-term existence of the population at a relatively stable size

ISSN 2075-5457 (print), ISSN 2220-9697 (online)

Alternative approaches to model design and refinement

The model was developed step by step through interactive discussions during student classes. Throughout this process, we identified several alternative developmental paths, some of which laid the groundwork for parallel model versions separate from the one focused on here. The points below summarize these potential directions for model adjustment.

Firstly, time lags could be introduced not only into how the global population reacts to environmental shifts but also into how the environment responds to population changes.

Furthermore, the global population could be split into two or more subpopulations with differing lag periods. One segment might respond much faster than the rest, with a dynamic ratio between these groups. This concept demonstrates the idea of societal heterogeneity: its different components adapt to new conditions in distinct ways.

The method for evaluating technological progress was a subject of debate. In our current implementation, progress is represented as a sustained increase in carrying capacity. However, it could also be assessed based on the state of the global population (for instance, its long-term, gradual growth without fluctuations in size).

Another open question is the unrestricted growth of carrying capacity due to culturally evolved lifestyle shifts, which characterises the current model version. An upper limit on carrying capacity could be introduced (representing the absolute ceiling of human population the planet can sustain under any lifestyle). This constraint should not act instantaneously, though the exact mechanism requires further definition. Alternatively, a ***Stability*** parameter could be introduced to pull the carrying capacity back toward its baseline value K_0.

We believe it would be highly productive to account for the Jevons paradox (Jevons, 1866), which posits that improvements in resource efficiency actually accelerate total consumption.

It should be noted that even at step 5, the simulated population dynamics deviate substantially from actual historical trends of global humanity. The most crucial difference is that real-world demographic shifts occur at a much slower pace, preventing the population from entering periodic oscillation cycles. However, further application of the chosen approach and the addition of new regulatory mechanisms could likely make the model population dynamics more adequate for studying human history. Is such a model valuable when its highly simplified regulatory feedback loops lead to less-than-perfect predictive accuracy? We argue that it is. The primary value of this model lies in its ability to isolate and determine the effects of each applied mechanism.

One way to overcome this limitation is to divide the global population into a certain number of subpopulations, each with its own dynamics. This concept can be expanded by incorporating population redistribution across groups (migration) and resource reallocation (transferring parts of unused carrying capacity, factoring in a certain efficiency loss).

Segmenting the global population into distinct subpopulations opens up the possibility of modelling varied developmental stages, each yielding an incremental boost to carrying capacity. For instance, several "phase transitions" can be identified in this process. Beginning with a baseline state (an opportunistic hunter-gatherer), a series of technological revolutions can be introduced, such as "Prometheus" (the use of fire), "Gaia" (the agrarian transition), "Hephaestus" (iron tools), "Hermes" (roads, logistics, trade), "Aeolus" (the steam engine), and "Zeus" (electrification).

Conclusions

The "Humanity Growth" model evolved as a hands-on pedagogical experiment, co-developed alongside Master's and PhD students within a simulation modelling course at V. N. Karazin Kharkiv National University. Our primary goal was not to deliver a forecasting tool, but rather to design an intuitive, modular framework that allows users to clearly trace how demographic and ecological factors drive complex system behaviour.

The step-by-step complication of the model architecture – progressing from basic Malthus exponential growth to integrating the Verhulst, Nicholson, and Notestein parameters – enabled us to evaluate each feedback loop in isolation. Our findings confirm that even against a background of culturally driven capacity expansion, response delays remain a critical vulnerability that can plunge the system into overshoot and crisis. The model also shows that the beginning of the demographic transition (when death rates drop but birth rates stay high) can be a highly unstable phase on the way to long-term stability.

Due to the intentional simplification of our baseline algorithms, the simulated population dynamics depart from the much smoother history of real humanity. However, this very simplicity removed distracting noise and made the underlying feedback loops easy to see. The current model framework serves as an open platform for future refinement, such as introducing subpopulations, migration dynamics, or Jevons' paradox. Finally, designing, critiquing, and testing this model together with Master's and PhD students proves that this interactive format is an exceptionally productive pedagogical tool within biosystem simulation modelling curricula.

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Appendix 1

```
# HUMAN POPULATION DYNAMICS (TYPE I MODEL).
# The model covers five steps of increasing complexity in the regulation of human population. Only females are modelled.
The step is chosen by a single parameter step (from 1 to 5). Each subsequent step includes all mechanisms of the previous ones.
# STEP 1: LOGISTIC REGULATION — resource limitation through K (carrying capacity). Population approaches K and stabilizes there.
# STEP 2: + LAG EFFECT — population responds to its own size with a delay of Lag years, which generates oscillations and possible overshoots of K.
# STEP 3: + ENVIRONMENTAL EXHAUSTION — when N exceeds K, K itself degrades ("Easter Island effect"). It recovers slowly when N <= K.
# STEP 4: + CULTURAL EVOLUTION — K grows each cycle by an amount proportional to the population size, producing hyperbolic growth due to lifestyle optimization.
# STEP 5: + DEMOGRAPHIC TRANSITION — sustained growth of K first reduces mortality, then (after a delay) fertility.
# INITIAL SCRIPT COMMANDS:
rm(list = ls()) # Clear the environment of previous variables
seed_value <- 12345 # NA for a random run, or an initial value of the random number generator for reproducibility
if (!is.na(seed_value)) set.seed(seed_value)
# E_N_T_R_A_N_C_E
# STEP SELECTION (from 1 to 5):
step <- 5
if (!step %in% 1:5) stop("step must be an integer from 1 to 5") # Validity check
use_lag <- step >= 2 ; use_exhaustion <- step >= 3; use_culture <- step >= 4; use_demographic <- step >= 5 # Derived logical flags...
# MAIN PARAMETERS:
n_classes <- 9 # number of age classes in the model
age_step <- 7 # duration of one age class in years; all classes have equal duration
b <- c(0.00, 0.00, 0.90, 0.70, 0.50, 0.40, 0.00, 0.00, 0.00) # Baseline fertility b[i] — expected number of newborn females per female of class i per year
d <- c(0.2, 0.1, 0.05, 0.04, 0.06, 0.1, 0.2, 0.3, 1.00) # Baseline mortality d[i] — probability of death of an individual of class i per year
N0 <- 500 # Initial number of females in the population
# EXPERIMENTAL CONDITIONS:
cycles <- 1200 # Simulation length in years
# time_points_custom <- c(0, 300, 329, 400, 430) # Optionally uncomment and specify 3 to 7 cycle numbers to be displayed on the Age structure diagram; if commented out, 4 default points are used (0%, 25%, 50%, 100% of cycles)
if (!exists("time_points_custom")) time_points_custom <- NULL
# PARAMETERS USED IN CERTAIN STEPS
# Logistic regulation parameters (step 1, always active regardless of step):
K_max <- 5000 # Verhulst parameter: initial carrying capacity; the number of females that the environment can sustain without degradation. In steps 1–3 it is a constant; in steps 4–5 K can grow due to cultural evolution
K_min <- K_max * 0.1 # Absolute lower bound for K (1% of K_max); guards against unbounded decline
crowd_d <- 0.02 # Intensity of crowding effect on mortality; as N approaches K, mortality increases by (1-d)*crowd_d; if crowd_d=0, regulation occurs only through fertility limitation
# Lag parameter (step 2 and above; ignored if step < 2):
Lag <- 35 # Conventional name: Nicholson's parameter; the number of years by which the population's response to its own size is delayed
# Exhaustion parameters (step 3 and above; ignored if step < 3):
Exh <- 0.3 # Conventional name: Easter Island parameter; intensity of environmental exhaustion when N exceeds K, according to K_new = K*(1 - Exh*(N-K)/K); larger Exh means faster environmental degradation during overpopulation crises
Recov <- 0.003 # Rate of slow recovery of K toward K_max when N <= K; must be significantly smaller than Exh, as exhaustion is faster than recovery
# Cultural evolution parameters (step 4 and above; ignored if step < 4):
```

```
Rise <- 0.001 # Conventional name: von Foerster's parameter; intensity of cultural evolution that depends on the number of "inventors"; K grows by Rise*N per cycle, producing hyperbolic growth of humanity: the more people, the faster cultural evolution proceeds
# Notestein parameters, demographic transition (step 5; ignored if step < 5):
Stable_dyn <- 200 # Window length (cycles) for detecting sustained dynamics of K, filtering out short-term fluctuations
min_dyn <- 0.05 # Threshold of relative change in K over Stable_dyn; if K grew by min_dyn — sustained demographic progress; if K fell by min_dyn — demographic crisis
Trans_lag <- 50 # Delay (cycles) between the start of stage 1 (mortality decline) and stage 2 (fertility decline)
Decl_d <- 0.2 # Maximum relative decline of mortality at full demographic transition (0.7 means d may fall to 30% of baseline)
Decl_b <- 0.55 # Maximum relative decline of fertility at full demographic transition
Decl_speed <- 0.02 # Speed of demographic transition per cycle (at 0.01 a full transition takes about 100 cycles)
# W_O_R_K_S_P_A_C_E
# GENERAL OBJECTS CREATION:
N <- round(rep(N0 / n_classes, n_classes))
N[1] <- N0 - sum(N[-1]) # Initial uniform distribution of N0 individuals across age classes
K <- K_max # current carrying capacity; starts from K_max
progress_d <- 0 # current progress of mortality decline due to demographic transition
progress_b <- 0 # current progress of fertility decline due to demographic transition
stage1_t <- NA # cycle at which the progress trigger (stage 1) was first activated
collapsed <- FALSE; collapse_t <- NA # Population collapse flags
Results <- matrix(NA, nrow = cycles + 1, ncol = n_classes + 4, dimnames = list(0:cycles, c(paste0("class_", 1:n_classes), "N_total", "K", "progress_d", "progress_b"))) # Matrix to store the full state of the system at every cycle
Results[1, ] <- c(N, sum(N), K, progress_d, progress_b) # Fill the first row of Results
# USERS FUNCTION CREATION:
update_K <- function(K, N_total, K_max, K_min, Exh, Recov, Rise, step) { # Update K for one cycle
 switch(as.character(step),
 "1" = K, # For step 1 K is constant
 "2" = K, # For step 2 K is constant
 "3" = { # Step 3: exhaustion or slow recovery
 if (N_total > K) { K_new <- K * (1 - Exh * (N_total - K) / K) # Relative exhaustion: scales with current K
 } else { K_new <- K + Recov * (K_max - K) } # Slow return to K_max
 max(K_min, K_new) }, # Lower bound for K
 "4" = , # Step 4 uses the same logic as step 5 (switch syntax: an empty branch passes control to the next one)
 "5" = { # Steps 4 and 5: exhaustion/recovery + cultural evolution
 if (N_total > K) { K_new <- K * (1 - Exh * (N_total - K) / K) + Rise * N_total # When N > K: exhaustion is proportional to relative overshoot, cultural growth is proportional to the number of inventors
 } else if (K < K_max) { K_new <- K + Recov * (K_max - K) + Rise * N_total # When N <= K and K < K_max: natural recovery toward K_max + cultural growth proportional to N
 } else { K_new <- K + Rise * N_total } # When N <= K and K >= K_max: only cultural growth, determined by the population size
 max(K_min, K_new) } ) }
check_progress_trigger <- function(K_history, t, Stable_dyn, min_dyn) { # Check for sustained growth of K (to start the demographic transition)
 if (t <= Stable_dyn) return(FALSE) # Until enough history has accumulated, the trigger cannot fire
 K_now <- K_history[t + 1] # Current K (at cycle t)
 K_past <- K_history[t + 1 - Stable_dyn] # K Stable_dyn cycles ago
 if (is.na(K_now) || is.na(K_past) || K_past <= 0) return(FALSE) # Guard against NA and zero values
 return(K_now > K_past * (1 + min_dyn)) } # Progress condition: K grew by the required percentage
check_crisis_trigger <- function(K_history, t, Stable_dyn, min_dyn) { # Check for sustained decline of K (a crisis that reverses the demographic transition)
 if (t <= Stable_dyn) return(FALSE)
 K_now <- K_history[t + 1]
 K_past <- K_history[t + 1 - Stable_dyn]
 if (is.na(K_now) || is.na(K_past) || K_past <= 0) return(FALSE)
 return(K_now < K_past * (1 - min_dyn)) } # Crisis condition: K fell by the required percentage
full_cycle <- function(N, b_dem, d_dem, n_classes, age_step, K, crowd_d, N_lag) { # One full cycle of the model (1 year of population life)
 N_new <- numeric(n_classes) # Final N vector
 N_surv <- numeric(n_classes) # Survivors
 N_staying <- numeric(n_classes) # Those who stayed in their class
 N_aging <- numeric(n_classes) # Those who moved to the next class
 free <- (K - N_lag) / K # Fraction of free environmental capacity; negative when N_lag > K (overpopulation crisis)
 b_eff <- pmin(b_dem, pmax(0, d_dem + (b_dem - d_dem) * free)) # Effective fertility: linear interpolation between d_dem (at N_lag=K) and b_dem (at N_lag=0)
 d_eff <- pmin(1, pmax(d_dem, d_dem + (1 - d_dem) * (1 - free) * crowd_d)) # Effective mortality: rises as N_lag -> K through crowd_d, even more when N_lag > K
 for (i in 1:n_classes) {N_surv[i] <- rbinom(1, size = N[i], prob = 1 - d_eff[i]) } # Binomially stochastic mortality: each individual of class i survives independently with probability (1 - d_eff[i])
 for (i in 1:n_classes) { # Binomially stochastic aging. Each living individual moves to the next class with probability 1/age_step
 N_aging[i] <- rbinom(1, size = N_surv[i], prob = 1 / age_step)
 N_staying[i] <- N_surv[i] - N_aging[i] }
```

 ISSN 2075-5457 (print), ISSN 2220-9697 (online)

```
 newborns <- sum(sapply(1:n_classes, function(i) rpois(1, lambda = N_surv[i] * b_eff[i]))) # Poisson-distributed births (sum of random newborn counts across classes)
 N_new[1] <- newborns + N_staying[1]
 for (i in 2:n_classes) { N_new[i] <- N_staying[i] + N_aging[i - 1] } # Assemble the final vector (class 1 = newborns + those who stayed in class 1; classes 2..last = those who stayed in their class + those who moved up from the previous class; individuals leaving the last class are lost)
 return(N_new) }
# W_O_R_K_F_L_O_W
# MAIN WORK CYCLE:
for (t in 1:cycles) {
 if (use_lag) { # The N value to which the population "responds" in this cycle; if use_lag=TRUE from history, otherwise current
 lag_row <- t - Lag
 if (lag_row < 1) { N_lag <- N0 # Until enough history has accumulated — initial N value
 } else { N_lag <- Results[lag_row, "N_total"] } # N_total from cycle t-Lag
 } else { N_lag <- sum(N) } # Without lag: current N
 if (!collapsed) { # K dynamics stop together with the population: without people there is no cultural evolution and no environmental impact
 K <- update_K(K, sum(N), K_max, K_min, Exh, Recov, Rise, step) }
 Results[t + 1, "K"] <- K # Store K in any case (for correct plots — a frozen line after collapse)
 if (use_demographic) { # Demographic transition only in step 5
 progress_trigger <- check_progress_trigger(Results[, "K"], t, Stable_dyn, min_dyn) # Check the triggers based on K history
 crisis_trigger <- check_crisis_trigger(Results[, "K"], t, Stable_dyn, min_dyn)
 if (progress_trigger) { # Mortality changes (grows during sustained progress, falls during sustained crisis)
 if (is.na(stage1_t)) stage1_t <- t # Record the start of changes
 progress_d <- min(1, progress_d + Decl_speed)
 } else if (crisis_trigger) { progress_d <- max(0, progress_d - Decl_speed)
 if (progress_d == 0) stage1_t <- NA } # Reset the marker when changes stop
 stage2_active <- progress_trigger && !is.na(stage1_t) && (t - stage1_t >= Trans_lag) # Fertility changes (if mortality changes have lasted Trans_lag cycles)
 if (stage2_active) { progress_b <- min(1, progress_b + Decl_speed)
 } else if (crisis_trigger) { progress_b <- max(0, progress_b - Decl_speed) }
 d_dem <- d * (1 - Decl_d * progress_d) # Demographic correction of mortality
 b_dem <- b * (1 - Decl_b * progress_b) # Demographic correction of fertility
 } else { d_dem <- d; b_dem <- b } # Without demographic transition
 if (!collapsed) { # Life cycle of the population, if it has not collapsed
 N <- full_cycle(N, b_dem, d_dem, n_classes, age_step, K, crowd_d, N_lag)
 if (sum(N) < 1) { message("Population collapsed at cycle ", t)
 collapsed <- TRUE; collapse_t <- t
 N <- rep(0, n_classes) } } # If the population has collapsed, N remains zero and K is frozen at the last value
 Results[t + 1, ] <- c(N, sum(N), K, progress_d, progress_b) } # Store the full system state in Results
# F_I_N_I_S_H_I_N_G
# RESULTS VISUALIZATION:
step_label <- switch(as.character(step), # Step name for the plot title
 "1" = "1: Logistic regulation",
 "2" = "2: Logistic regulation + lag effect",
 "3" = "3: Logistic regulation + lag + environmental exhaustion",
 "4" = "4: Logistic regulation + lag + exhaustion + cultural evolution",
 "5" = "5: Logistic regulation + lag + exhaustion + cultural evolution + demographic transition" )
age_labels <- paste0(seq(0, (n_classes - 1) * age_step, by = age_step), "-",
 seq(age_step - 1, n_classes * age_step - 1, by = age_step)) # Age class labels for the X axis of the age structure plot
params_line1 <- paste0("K_max=", K_max, ", crowd_d=", crowd_d, ", N0=", N0, ", cycles=", cycles,
 if (!is.na(seed_value)) paste0(", seed=", seed_value) else "") # Title line 1: general parameters
params_line2 <- "" # Title line 2: parameters of the mechanisms active at the current step
if (step >= 2) params_line2 <- paste0(params_line2, "Lag=", Lag, " ")
if (step >= 3) params_line2 <- paste0(params_line2, "Exh=", Exh, ", Recov=", Recov, " ")
if (step >= 4) params_line2 <- paste0(params_line2, "Rise=", Rise, " ")
if (step >= 5) params_line2 <- paste0(params_line2, "Decl_d=", Decl_d, ", Decl_b=", Decl_b, ", Decl_speed=", Decl_speed, ", Trans_lag=", Trans_lag)
b_label <- if (step == 5) "Baseline b" else "b" # Title lines 3-4: b and d vectors across age classes; for step 5 these are baseline values
d_label <- if (step == 5) "Baseline d" else "d"
params_line3 <- paste0(b_label, ": ", paste(paste0(age_labels, "=", b), collapse = " "))
params_line4 <- paste0(d_label, ": ", paste(paste0(age_labels, "=", d), collapse = " "))
title_text <- paste0("Step ", step_label, "\n", # Single title with line breaks
 params_line1,
 if (nchar(params_line2) > 0) paste0("\n", params_line2) else "",
 "\n", params_line3, "\n", params_line4)
if (use_demographic) { # Window layout: top row — title, below — plots (three for step 5, two for steps 1-4)
 layout(matrix(c(1, 1, 1, 2, 3, 4), nrow = 2, byrow = TRUE), heights = c(0.18, 1))
```

```
} else { layout(matrix(c(1, 1, 2, 3), nrow = 2, byrow = TRUE), heights = c(0.18, 1)) }
par(mar = c(0, 0, 0, 0)) # Panel 1: title with all parameters and b, d vectors
plot.new()
text(0.5, 0.5, title_text, cex = 1, font = 1, adj = c(0.5, 0.5))
par(mar = c(4, 4, 2, 1)) # Panel 2: population dynamics and K dynamics
y_max <- max(max(Results[, "N_total"], na.rm = TRUE), max(Results[, "K"], na.rm = TRUE)) * 1.05
plot(0:cycles, Results[, "N_total"],type = "l", lwd = 2, col = "darkblue", ylim = c(0, y_max), xlab = "Time (years)", ylab = "Total
females / K", main = "Population dynamics")
lines(0:cycles, Results[, "K"], lwd = 2, lty = 2, col = "red") # Dynamic K — dashed red line
if (!is.na(collapse_t)) abline(v = collapse_t, lty = 3, col = "grey40") # Mark the moment of collapse, if any
legend("topleft", legend = c("N total", "K (dynamic)"),col = c("darkblue", "red"), lty = c(1, 2), lwd = 2, cex = 0.85)
if (is.null(time_points_custom)) { # If custom time points are not specified — default 4 points
 time_points_marks <- round(c(1, cycles / 4, cycles / 2, cycles), 0)
} else { time_points_marks <- time_points_custom + 1 } # Custom moments + 1 (since row 1 of the matrix corresponds to t=0)
time_points_marks <- time_points_marks[time_points_marks >= 1 & time_points_marks <= cycles + 1] # Guard against out-
of-range values
if (length(time_points_marks) < 3 || length(time_points_marks) > 7) stop("time_points_custom must contain 3 to 7 values
within [0, cycles]") # Check count
colors_palette <- c("blue", "green3", "orange", "red", "purple", "brown", "magenta") # Up to 7 colors
colors_marks <- colors_palette[seq_along(time_points_marks)]
points(time_points_marks - 1, rep(y_max * 0.94, length(time_points_marks)), pch = 25, bg =
colors_marks[seq_along(time_points_marks)], col = colors_marks[seq_along(time_points_marks)], cex = 1.5)
grid()
if (use_demographic) { # Panel 3 (if use_demographic=TRUE)
 par(mar = c(4, 4, 2, 1))
 plot(0:cycles, Results[, "progress_d"], type = "l", lwd = 2, col = "purple", ylim = c(0, 1.05), xlab = "Time (years)", ylab =
"Progress (0..1)", main = "Demographic transition")
 lines(0:cycles, Results[, "progress_b"], lwd = 2, lty = 2, col = "darkgreen")
 legend("topleft", legend = c("progress_d (mortality)", "progress_b (fertility)"), col = c("purple", "darkgreen"), lty = c(1, 2), lwd = 2, cex
= 0.85)
 grid() }
par(mar = c(5, 4, 2, 1)) # Final panel: age structure at the chosen time points
matplot(1:n_classes, t(Results[time_points_marks, 1:n_classes]), type = "b", pch = 16, lwd = 2, col =
colors_marks[seq_along(time_points_marks)], xaxt = "n", xlab = "Age class", ylab = "Number of females", main = "Age
structure")
axis(1, at = 1:n_classes, labels = age_labels, las = 2, cex.axis = 0.7)
legend("topright", legend = paste0("t=", time_points_marks - 1), col = colors_marks, lty = seq_along(time_points_marks),
pch = 16, cex = 0.8)
grid()
layout(1) # Return to the default graphical layout
```

Від пастки Мальтуса до демографічного переходу: освітні та наукові аспекти університетського курсу з моделювання

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У статті описано імітаційну модель, що стала результатом спільної роботи магістрантів, аспірантів та викладачів у рамках курсу «Імітаційне моделювання стійкості та еволюції надорганізмових біосистем». У ході низки академічних занять у середовищі R було розроблено імітаційну модель «Зростання людства», яка характеризується поетапним збільшенням системної складності. Ця модель належить до категорії «моделей перевірки достатності механізмів» (моделей, що перевіряють, чи є запропоновані механізми достатніми для відтворення спостережуваної динаміки). Базова архітектура складається з моделі експоненціального зростання населення з кількома віковими класами, кожен з яких характеризується власними показниками народжуваності та смертності. На наступних етапах модель послідовно інтегрує: логістичне обмеження ємності середовища (параметр Ферхюльста); лаг-ефект ефект у реакції населення на дефіцит ресурсів (параметр Ніколсона); зменшення ємності середовища внаслідок криз перенаселення (параметр Острова Пасхи); зростання ємності середовища, зумовлене культурною еволюцією, що оптимізує спосіб життя (параметр фон Ферстера); і, нарешті, механізм демографічного переходу (параметр Ноустейна). Розглянуто структуру моделі, результати моделювання та альтернативні алгоритмічні рішення, які були запропоновані у ході спільної розробки. Автори вважають такий покроковий підхід до моделювання успішним і пропонують свій досвід для подальшого розвитку та застосування.

Ключові слова: *імітаційне моделювання, чисельність людства, динаміка чисельності, стійкість, ємність середовища, лаг-ефект, гіперболічне зростання, демографічний перехід, модель перевірки достатності механізмів*

***Цитування**: Nesterenko K.O., Holovnia D.O., Kravchenko M.O., Shorokhova E.A., Sydorova M.A., Surma O.S., Shabanov D.A. From Malthusian trap to demographic transition: educational and research aspects of a university simulation course. Вісник Харківського національного університету імені В.Н. Каразіна. Серія «Біологія», 2026, 46, 23–42. https://doi.org/10.26565/2075-5457-2026-46-3*

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Conflict of interest: The authors certify that although one of the authors of the article is the Editor-in-Chief of this journal, the peer-review process, the publication decision, and the editing process were conducted independently, without their participation or influence. The peer review and the final decision were carried out by other members of the editorial board who are not co- authors. Any potential conflicts of interest were fully mitigated through external oversight of the process. / **Конфлікт інтересів:** автори засвідчують, що, незважаючи на те, що один із авторів статті є головним редактором цього журналу, процес рецензування, прийняття рішення щодо публікації та редагування проводилися незалежно, без їх участі чи впливу. Рецензування, остаточне рішення ухвалювалося іншими членами редакційної колегії, які не є співавторами. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.

Use of Artificial Intelligence: The authors report that during the conduct of the study and the preparation of this manuscript, generative artificial intelligence (such as https://claude.ai/, etc.), under the authors' supervision, was used as a tool for writing the script in the R language, for translating text segments, and for checking the grammar of the article. All results of the use of artificial intelligence were reviewed and corrected by the authors, who assume responsibility for the final results. / **Використання штучного інтелекту:** Автори повідомляють, що під час проведення дослідження та підготовки цього рукопису генеративний штучний інтелект (https://claude.ai/ тощо) під контролем авторів було використано як інструмент для написання тексту скрипту на мові R, для перекладу фрагментів тексту та для граматичної перевірки тексту статті. Усі результати використання штучного інтелекту контролювалися та виправлялися авторами, які приймають на себе відповідальність за кінцевий результат.

Подано до редакції: 15.01.2026 / Прорецензовано: 21.03.2026 / Прийнято до друку: 25.04.2026 / Оприлюднено: 31.05.2026