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Revisiting *Limits to Growth*: A simple qualitative model unveils most global system trajectories

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Abstract

Fifty years after the publication of *Limits to Growth* (LtG), its scenarios predicting a global socio-economic collapse are still relevant. In this study, we extract the key components and processes from the Limits to Growth (LtG) narratives to construct a simple qualitative model. Our modeling framework enables the computation of all possible system trajectories (scenarios) within a single output, once the model accepted. By retracing all scenarios presented in LtG, our model uncovers highly interconnected trajectories leading to either sustainability or collapse. The simplicity of our approach allows focusing on 13 variables and 40 qualitative rules only. Through this work, we demonstrate that the co-authors of LtG successfully tackled the challenge of exhaustively representing all conceivable trajectories for the global system, grounded in their core assumptions. Furthermore, our study paves the way for exploring alternative scenarios by applying this comprehensive yet straightforward framework to newly acquired knowledge.

Introduction

Published in 1972, the book *Limits to Growth* (LtG; (D. H. Meadows et al. 1972) garnered significant attention for its exposition of the consequences of overshooting physical limits. LtG answered the concerns of the Club of Rome (King 1979) about the future of global economy in a context of ever-growing human population. It presents different scenarios produced from World3, a numerical model compiling hundreds of equations of demographical dynamics and non-renewable resources exploitation (Forrester 1971).

Each scenario depicted in LtG is conditioned by specific assumptions, such as the initial quantity of resources, the availability of pollution mitigation technologies, or advances in agricultural productivity. In most scenarios, the simulated world system experiences an overshoot of the Earth's *carrying capacity*, i.e., the number of human beings that can be sustained without irreversibly depleting resources. This overshoot invariably leads to a *collapse* - defined as an abrupt decrease of human population and/or production per capita, accompanied by a significant degradation of well-being (D. H. Meadows et al. 1972). Global system stabilization can only be reached in scenarios that envision a rational humanity, one that abandons the pursuit of perpetual industrial growth. LtG asserts that even technological solutions are insufficient to avert collapse, and can only delay it by a few decades.

Notice that LtG's objective was never to predict the future, neither to conclude on the most likely scenario, Rather, it aimed to emphasize the fact that a system driven by economic growth would inevitably encounter physical limits (D. Meadows, Randers, and Meadows 2004).

Upon its release, LtG's faced intense criticism for various reasons ranging from simple misunderstanding to outright rejection of its main assumptions. Economists criticized the predominance of demographics and the absence of prices and market expectations (Nordhaus 1973; Solow 1974; Stiglitz 1974), yet this was not sufficient to dismiss the central issue regarding the sustainability of the industrial development that LtG questioned (Pottier 2014). Several analysis addressed World3's flaws, including its "black box" effect and lack of robustness (Vermeulen and De Jongh 1976; Thissen 1978). However, these analyses often deviate from the model's realism and fail to adequately challenge its relevance (Plessix 2019).

The model has been updated twice with "Beyond the Limits" (Meadows et al., 1993) and "Limits to Growth: The 30-Year Update" (Meadows et al., 2004). Despite these corrections, the primary conclusions have remained consistent, with the authors growing increasingly alarmed over time. Recent comparisons of the LtG predictions with real-world observations

indicate that current global trajectories (pathways) closely align with scenarios predicting a collapse, while progressively moving away from stabilization (Turner 2008; Herrington 2021).

Until now, investigations into the structural dynamics of World3 have remained elusive, leaving a significant knowledge gap. Despite the current limitations in techniques, our study represents a significant stride towards bridging this gap. Given the prevailing global crisis, we firmly assert the utmost importance of fostering a comprehensive approach to comprehend diverse socio-ecological models.

Based on this observation, we proceeded with the extraction of major components from LtG's narrative, aiming for a parsimonious set of components while ensuring sufficient accuracy in their definition. To achieve this, we employed the Ecological Discrete-Event Network (EDEN) modeling framework, which has demonstrated its success in modeling natural ecosystems (Cédric Gaucherel and Pommereau 2019; C. Gaucherel, Pommereau, and Hély 2020; Cosme 2022; Thomas et al. 2022)

Within this framework, we translated each extracted component into a variable with two possible states, depending on its presence or absence in a significant quantity, determined by a predefined threshold. We then extracted the qualitative processes linking these selected variables from LtG's report, constructing an interaction network. The resulting model, named Eden3, enables exhaustive computation of all possible states of the system's variables. It starts from a pre-industrial initial state and progresses through the application of the selected processes.

To validate the model's accuracy, we transcribed each scenario from LtG into a chronological list of system states and thoroughly examined their presence in the model's output. It was our assumption that the EDEN modeling framework, chosen for its suitability in representing the LtG narrative, could encompass all World3 scenarios within a single output. This encompassment includes alternative transitions not explicitly considered in LtG's original work.

Results

1. Reproducing LtG with a parsimonious model

LtG's narratives have been effectively transcribed into Eden3, a qualitative model consisting of 13 binary-state variables. A detailed list of these variables and their corresponding thresholds can be found in the Supplementary Materials (Table S1 and S2). Each variable represents the translation of one or multiple components of World3, as outlined in LtG. Our

selection criteria ensured that each variable relates to a material stock within the real world. Certain entities from the original model have not been included in Eden3 due to their incompatibility with the criteria of simplicity and parsimony, as outlined in the Method section.

The interaction between variables occurs through 40 processes, all explicitly mentioned in LtG and represented by at least one equation in World3. In Eden3, these processes are expressed as rules, which consist of one or multiple condition(s) and the possible consequence on one or several variable(s). For a comprehensive list of these rules, refer to the Supplementary Materials. The resulting interaction network (Figure 1) provides a visual representation of the topological structure of the model, enabling a holistic understanding of the interactions between variables and their possible dynamics.

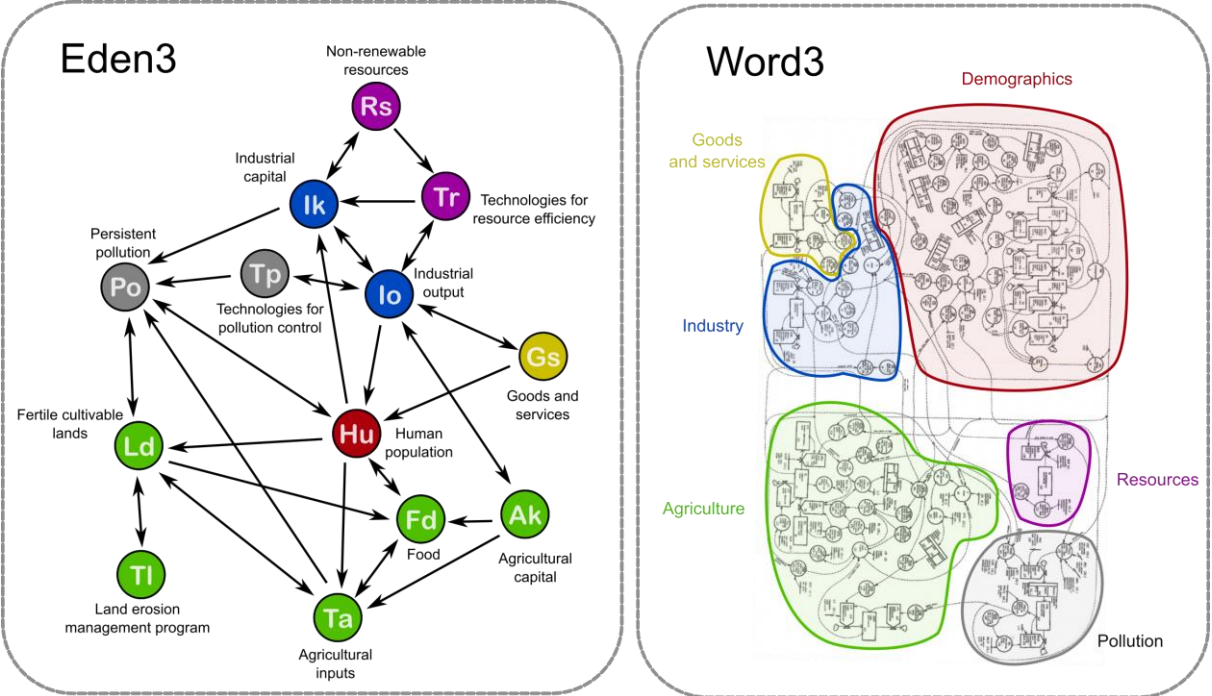


Figure 1. Simplification of Eden3’s interaction network (left), as compared to the original structure of the World3 model with highlighted modules (right). Each node corresponds to a variable, representing a component of LtG’s narratives. Each color corresponds to a major module (red: human population, purple: resources, blue: industry, green: agriculture, yellow: goods and services, grey: pollutions). Each edge represents one or multiple processes involving the interaction between variables: the edge tail represents the variable involved in at least one rule condition, and the edge head represents the possibly impacted variable. The original structure of the World3 model is colored by the six major modules (with the same colors in the Eden3 network).

Variables that exhibit connections with multiple other variables can be regarded as the most influential within the model, as they play a crucial role in shaping the system's dynamics. In Eden3, two components emerge as central: the human population and the industrial output.

In World3, the module concerning demography is highly intricate, incorporating four classes of ages that respond to mortality and fertility rates and social conventions. These classes, in turn depend on the food availability, manufactured goods, health services or pollution level. However, we introduced here a markedly simpler approach by utilizing a single component for global human population. This allowed to discriminate a system with a large population – comparable to our current world state – and a collapsed one with a population that has fallen under a specified threshold.

The industrial module has been reduced into two components. The central role is assumed by the industrial output variable, which represents the investment flow described in LtG. This investment can be allocated across various sectors, stimulating their expansion or compensating for their degradation by sustaining their functionality. Supporting the industrial output is the industrial capital, representing the quantity of machinery and infrastructure dedicated to industrial production and resource extraction. Eden3 mimics the industrial capital “death and birth” loops as described in LtG. As all products, buildings and machines, have a limited lifespan, their replacement rate must be greater than their depreciation rate to maintain industrial growth. The degradation of the industrial capital can occur if humans neglect to care for it or are unable to keep up with its deterioration, potentially triggering a cascading effect in other sectors of the system.

To adhere to our principle of parsimony, we have consolidated the production of goods and services into a single component within the model. This decision stems from the understanding that both goods and services contribute to human welfare. In World3, the concept of human welfare is derived from factors such as human life expectancy and gross domestic product per capita, which are influenced by both health services and industrial production.

Two distinct approaches coexist to ensure food supply from the agricultural sector. The first approach is “traditional” and relies on the existence of large amount of dedicated capital coupled with the availability of large surfaces of fertile cultivable lands. In the second approach, the model accounts for situations of limited availability of exploitable lands. To compensate for this constraint, the agricultural sector relies heavily on inputs such as chemical fertilizers or pesticides. However, this alternative method may lead to land erosion. The surface of productive land is assumed sensitive to overproduction, overcrowding (i.e., urbanization) and pollution.

Similar to World3, the persistent pollution component is detrimental on land quality and human population, and represents the aggregation of various sources of pollution. These include pollution generated by agricultural inputs, industrial capital (through resource exploitation) and human activity (such as solid waste from the use of manufactured goods and land transformation due to urbanization). Hence, carbon emissions are conceptually encompassed in this component.

As we mentioned earlier, all variables included in the model are Boolean. The activating threshold for each of them was set based on their respective values in the year 2000. This reference point establishes, for most used variables, a significant reduction of quantity compared to present values. A return to a level below these thresholds would reasonably be considered a recession, or worst, a collapse.

The pool of non-renewable resources occupied a peripheral position within the interaction network as it can only decrease. However, the initial amount of non-renewable resources plays a key role in determining the system's outcome. In LtG, scenarios one and two differ in the amount of the initial stock, ranging from simple to double. Indeed, the precise amount present in the crust of Earth cannot be estimated (Rockström et al. 2009). This disparity has significant implications for the fate of humanity, where collapse can be triggered either by a resource scarcity or a crisis resulting from pollution. Eden3 grasped the potential for different initial resource quantities by employing a different threshold corresponding to "half of the original amount available in the Earth's crust". The fall below this threshold can occur at any point when the industrial capital variable is present.

In LtG, technical solutions are gradually introduced in scenarios three to six, assuming that humans will invest into these technologies each time they encounter the problem, depending on their investment capacity. In Eden3, technical solutions were represented by effective components, albeit mostly peripheral: they were connected primarily to the variables that trigger their productions and the specific variables they were designed to address. There are four technologies: (i) agricultural inputs that enhance food production, (ii) pollution control technologies which serve to artificially mitigate existing pollution, (iii) land management program that safeguard lands against erosion, and (iv) a resource efficiency technology that gives the possibilities to human to extract remaining resources and minimize waste generation.

2. Narratives and collapse

The eleven scenarios presented in the most recent update of LtG (D. Meadows, Randers, and Meadows 2004) have been successfully translated into a chronological sequence of system states (Fig. 2, Table S3). To differentiate between the various system states, we used six synthetic variables, each representing the state of a specific module among human population (Hu), non-renewable resources (Rs), industrial output (Io), food (Fd), goods and services (Gs), and persistent pollution (Po). Each variable provides valuable information on the state of the global system, indicating whether they are present in substantial quantities (indicated by the variable “present”) or absent (indicated by the variable “absent”) within the system state.

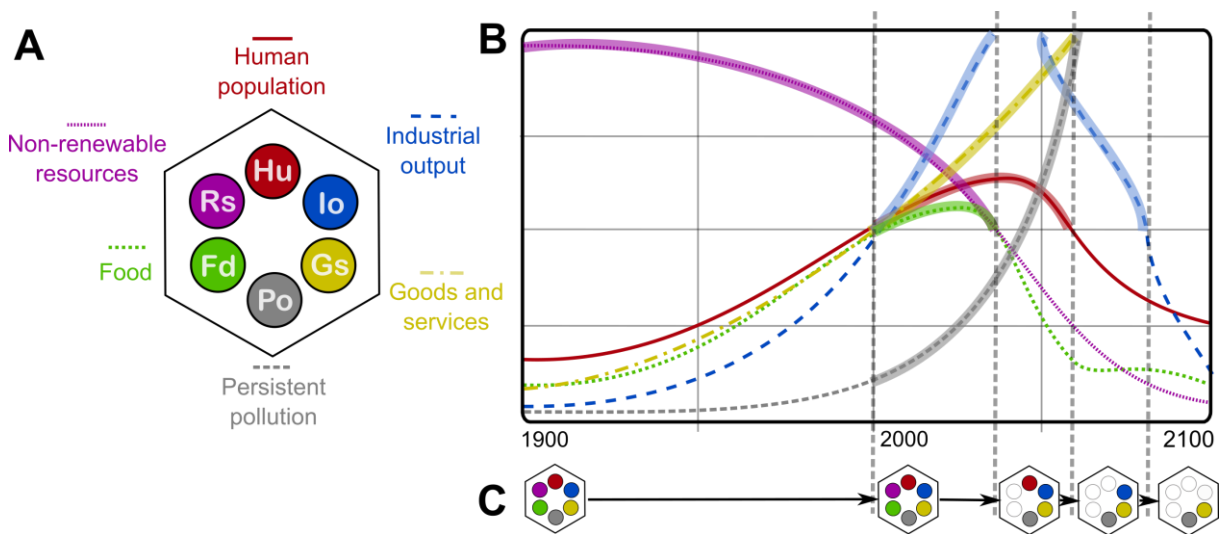


Figure 2. Using six synthetic variables (A), translation of the Scenario two of LtG (B) into Eden system states (C). Each hexagon represents a system state; or the assemblage of all variable states in Eden3. Variables can either be “present” when they are above their associated threshold (colored circles, highlighted curve) or “absent” when they are below their threshold (blank circles, fine curve). Thresholds correspond to the value of the corresponding variable in the year 2000.

The state transition graph (STG, Fig. 3) provides a comprehensive overview of all possible system states that can be reached, from the initial state and connected through possible transitions. Each transition corresponds to the activation of one process or many processes, previously encoded as formal (fired) rules. The Eden3 model grounds on logical processes. Hence, system states are chronologically ordered to represent sequences of events and to respect causality, while time is not temporized. Importantly, all sets of successive states derived from each LtG’s scenario were successfully recovered and predicted by Eden3.

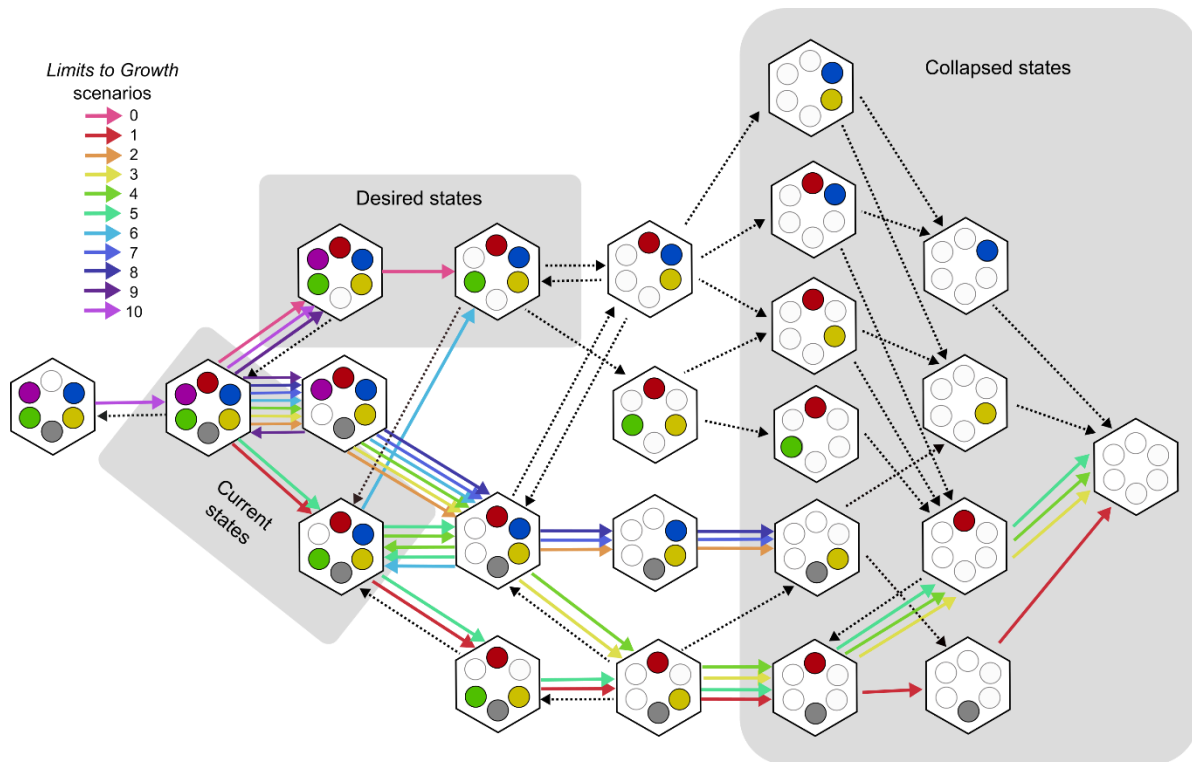


Figure 3. Simplification of the state transition graph provided by the Eden3 model. Each system state (hexagon, as defined in Fig.2A) is composed of the state of each variable (Round, colored: “present”, or above its threshold and blank: “absent” or below its threshold). Transitions between system states are represented by rules (Arrows, colored: present in LtG’s scenarios, dotted: not present in LtG’s scenario but possible according to Eden3’s dynamics).

Eden3’s comprehensive STG encompassed 5,268 distinct states, each representing a unique combination of the 13 variables. The STG originated from a pre-industrial initial state, characterized by abundant non-renewable resources and extensive fertile cultivable lands. In line with World3’s simulations starting in 1900, remaining variables were initially low, and gradually increased toward their threshold.

Eventually, the system may reach a state in which all six synthetic variables were activated. This state closely resembles the observed world state, and is comparable to the year 2000. We thus labeled this state the “current state” of the Global system. Nevertheless, the resource component exhibited a nuanced position, and could either be present or not depending on estimations.

Eden3 generated multiple trajectories between the initial state and the current state. Some trajectories unveil “past” trajectories in which industrial components were not present, at least not immediately.

Upon reaching the current state, the system branches into multiple trajectories mimicking possible future scenarios (EDEN3 may be called a possibilistic model). We considered a “desired” state as one that mimics the current state, but before the presence of pollution. Desired states can be reached from the current state by mitigating pollution with the use of pollution-control technologies. Desired states align with sustainable scenarios described in LtG. In Eden3, these states showed multiple descendants. State changes were still possible in the STG, and all of them implied either the loss of a desired component or the appearance of pollution.

Most states in the full STG exhibit extensive connectivity, enabling multiple cycling and reversing trajectories. Reversals, involving the re-activation of a previously suppressed component, such as industry, agriculture and services are mostly facilitated by technology components. This aligns with the narratives presented in LtG, where the reachability of a desired state requires the deployment of technological innovations.

For instance, the implementation of a land protection management program can facilitate the recovery of fertility in cultivated lands. But technological solutions may only give temporary respite. Recall that the dynamics of investments imply that the industrial output is switched off, technology components may follow suit.

Certain trajectories lead to a terminal basin, which designates a set of states that share the same descendants. This terminal basin contains system states corresponding to the collapsed states depicted in LtG’s scenarios, and most trajectories converge towards this basin (Fig. 3). The critical factor driving the transition is the variable of non-renewable resources. As the precise quantity of extractable resources from the Earth’s crust remains uncertain, the loss of that component can occur at any time, as long as the industrial capital component, representing resource exploitation, is present.

The absence of the non-renewable resource component can trigger a cascading effect throughout the system, starting with the industrial components. Eventually, the replacement rate of industrial capital can exceed the depreciation rate, spreading this dynamics over agricultural and services sectors. The system gets trapped into a terminal basin with most components absent, with the exception of fertile cultivable lands that have the potential to regenerate over time. Once the system reaches this basin, indicator variables are unable to regain their thresholds, implying an irreversible state of collapse.

Discussion

A parsimonious and qualitative model, *Eden3*, demonstrated in this study the exhaustive nature of the scenarios outlined in the Limits to Growth (LtG) report. By extracting the essential representation of the global socio-ecosystem intentionally modeled with *World3*, *Eden3* strikes a balance between richness and simplicity, allowing for structural analysis and interpretation of the resulting outputs. The language (syntax) used in our model is natural, transparent, and sufficiently straightforward to allow for the objective identification of critical variables and processes within *World3*.

The major results of *Eden3* aligned with the conclusions deduced 50 years ago in LtG. By being faithful to the original narrative, human population and industrial sectors remain central components of the system (Honti *et al.* 2019). The finite nature of resources and their roles in reaching a possible collapse without redemption highlights the importance of managing resource limitations. Technology remains peripheral, opens possibilities for reversals but only provides temporary delays to collapse (Fig. 3)(D. H. Meadows *et al.* 1972). It addresses symptoms rather than core issues.

Eden3 introduced an important nuance regarding the desirable “sustainable” states described in LtG. While these states can be identified and reached, they were neither ineluctable nor definitive in the modeled dynamics. In this possibilistic model, they were only “possible”, and it is up to the global society to make them genuinely sustainable. Conversely, collapsed states belong to a basin of unredeemed states (i.e. no process/rule can push the system to left them).

All these findings and the ability to reproduce qualitatively any scenario depicted in LtG have been achieved by breaking down the hundreds of equations and parameters to 13 critical thresholds of synthetic stocks and 40 possibilistic processes (Fig. 1 and Tables S1-S2). With such a simplicity, we were not able to elicit a potentially missed trajectory that had not been identified by LtG and its authors. Rather, we were comforted in the idea that the 11 trajectories presented in the book provide a comprehensive overview of the possible patterns, transitions and final outcomes, given the fundamental structure and assumptions of *World3*. This highlights the authors' commendable efforts in presenting nearly all the patterns of the Global socio-ecological system using a complex deterministic model, relying on their intuition to select inputs producing relevant scenarios illustrating the dynamic behaviors of *World3* (Table S3).

Recent advances in modelling, such as Integrated Assessment Models (Rozenberg *et al.* 2014), coupled with the exponentially growth of computing power and the collection of huge

databases, have pushed forward a “black box” quantitative approach to designing prospective trajectories or understanding resilience, tipping points and collapses. Our modelling philosophy contrasts with that of differential systems such as World3 and its heirs. We were not able to provide quantitative predictions or continuous trajectories. Instead, time was here logical rather than physical, variables were synthesized by critical thresholds, and transitions were possible without any assertion of likelihood.

In counterpoint, we balanced this abstraction with the ability to exhaust the combinatorics of possible trajectories and by picturing the State Transition Graph, that is, the illustrated qualitative structure of the modeled dynamics (Cédric Gaucherel and Pommereau 2019; C. Gaucherel, Pommereau, and Hély 2020). Sustainable regimes and collapsed worlds are connected in an explicit manner by analyzing this graph, which reveals a deeper understanding of complex interdependencies.

By the way, our study demonstrated the potential applications of possibilistic models as a complementary approach based on simplicity and exhaustivity. Presently, we do not depart from the assumptions of a predefined model, and relying on World3 accuracy and relevance exposes this study to the same criticisms. But the Eden framework has been tested in genuinely new applications with unique representations (Cosme 2022; Thomas et al. 2022). We are therefore optimistic about the prospect of using ecological and economic possibilistic models for the understanding of systems that are still lacking a formal approach.

Lastly, a meticulous examination of the State Transition Graph (STG) in Eden3 reveals no significant novel pathways that are not already encompassed within the 11 studied scenarios. These scenarios thoroughly explore the interpretation of the model, leaving aside the cycles and repetitions mentioned earlier. If Eden3 faithfully represents the fundamental structure of World3, which we argued for in the previous section, one is inclined to conclude that the authors of LtG have provided a sufficiently comprehensive analysis of World3 through these 11 scenarios.

The criticism of World3 being a black box and the lack of control over such a complex system have always raised concerns regarding potential hidden information processing from the numerical analysis in LtG. However, our exhaustive study of the simple yet faithful transcription in Eden3 tips the scales in favor of the LtG report, suggesting that it does not lack any crucial angles or perspectives.

Methods

The EDEN framework

In this study, we employed the EDEN (Ecological Discrete-Event Network) framework (C. Gaucherel, Pommereau, and Hély 2020; Pommereau, Thomas, and Gaucherel 2022) to achieve our objectives. EDEN incorporates possibilistic, qualitative, discrete event and asynchronous update mode that align well with the original purpose of the Limits to Growth (LtG) reports (D. H. Meadows et al. 1972; D. H. Meadows, Meadows, and Randers 1993; D. Meadows, Randers, and Meadows 2004). It allows an arbitrary exploration of a wide range of trajectories without providing information on the likelihood of one scenario over another. However, it ensures exhaustiveness by encompassing all possible system outcomes within a single output, once the modeled has been accepted (Cédric Gaucherel and Pommereau 2019; C. Gaucherel, Pommereau, and Hély 2020).

Unlike models such as World3, EDEN does not incorporate a physical timeline or rely on quantitative variables, which is difficult to calibrate and can be unreliable. Instead and without sacrificing clarity, it provides a comprehensive overview of the system transitions using asynchronous update handling concurrent causal processes. Finally, EDEN computes all possible transitions (from a chosen initial state) and their sequences, which are then visually emphasized.

EDEN Incorporates variables and rules. Variables are Boolean and can take the value “present / above a threshold” (+) or “absent / below a threshold” (-). They represent tangible interacting components of the modeled system, preferably existing physical stocks by focusing on critical quantity. This approach facilitates a clear and unambiguous conceptualization, enabling a more accurate interpretation of rules. The Boolean values relate to a critical predefined threshold of the represented component then involved into a causal process. This threshold can be theoretical or arbitrary, or calibrated, estimated from data, expert judgment and guesstimate, but it is unique for each variable in the same model. This does not restrict the interpretation to strict binary states of real-world. For instance, we fix a threshold of roughly six billions for the human population (Hu), where Hu+ refers to a sufficiently large population to activate additional effects (rules) within the system, while Hu- refers to a lower population.

Rules that are connecting variables represent the processes connecting subsets of the system components. Rules take a condition (left), i.e., values for a subset of variables, and provide a realization (right), i.e., another set of values for a subset of variables. Taking back the previous example, the rule

Io+ >> Hu+

formalizes the process that “a significant amount of industrial output (Io+) *may allow* humanity to grow over six billions heads”. Emphasize is put here on the fact that each causal process is possibilistic, meaning that the rule may apply yet not necessarily. Put differently, the rule outcome is computed twice in EDEN, with a probability strictly equal to 0 *and* to 1. Accordingly, rules are not weighted and do not impose priority of application: they are fired in parallel (called *concurrency*). The modeler may want a rule to apply (almost) systematically, i.e., without the probability of 0. Such rules are labeled *constrains*, and by definition, they have priority over any other rule.

A system state is a vector of values for all variables of the modeled system. An *initial state* is a predefined state referring to the starting point of application of rules; the model is fully determined by the set of variables, constrains and rules. The analysis necessitates the initial state, but it can also provide comparative analysis for multiple distinct initial states. An example of a simple three-variable EDEN model is available in Supplementary materials (Fig. S1).

EDEN is exploited via *Ecco*, a software with a Python interface (available at <https://github.com/fpom/ecco>) handled under a Jupyter platform, only available online through the Evry University server with restricted access. Ecco uses the set of rules and the initial state to compute all possible chronological changes successively reached by the modeled system. The set of all reachable system states is gathered into a State Transition Graph (STG) which encompasses the system states and all the transitions (involving one or several activated rules) connecting them (e.g., Fig. 3). The combinatory nature of the STG can rapidly become overwhelming and often remain implicit (i.e., the whole STG is computed and stored yet not displayed). Ecco provides graphical options to aggregate and disaggregate subsets of the STG according to one or several discriminating variables or rules (C. Gaucherel, Pommereau, and Hély 2020; Pommereau, Thomas, and Gaucherel 2022). An example of STG produced by ecco with the Eden3 model is available in Supplementary materials (Fig. S2).

Variables and rules can also be displayed by using a more static view, consisting in a graph approximating the network of interactions (Fig. 1, left panel). In this network, nodes represent variables. Directed edges combine two variables in the condition and the realization, respectively, in one or several rules. The simplified interaction graph can still help extract information, such as modularity of the system or “centrality” and periphery of components.

Modeling choices for Eden3:

1. Choice of variables and rules

We primarily rely on the latest update of LtG (Meadows et al., 2004) and the available online version of World3. In selecting variables and rules for the Eden3 model, we applied three criteria. Firstly, an Eden3 variable must refer to an explicitly stated variable found in LtG, and be represented by a variable or group of variables in World3. Secondly, variables must represent material stocks. We favored stocks such as a quantity of industrial output over rates or ratios such as stocks per capita or production per unit of time. Components that are *a priori* intangible, like services, are preferably represented by a material quantity of buildings or equipment (e.g., that are associated with services provision, like schools and hospitals), in order for the system states to remain understandable and measurable. Furthermore, since World3 outputs are in the form of quantifiable stock curves, using the same components facilitated the validation of Eden3 by enabling direct comparison to the original scenarios.

The third criterion we apply is parsimony. For the sake of simplicity, we discarded components that were redundant in their interaction with other components. For example, both service capital and manufactured goods are produced through industrial output, and both contribute to human welfare (i.e., without differential impacts). Therefore, we merged these components into a single variable (Table S1, Supplementary Materials).

After the selection of the global components and variables in Eden3, we chose the associated processes from the LtG narratives and translated them into formal rules in Eden3 (Table S2, Supplementary Materials). Each rule consists in a condition and a realization, both of which had to be justified by at least one sentence in LtG report. Rules obey the same criteria of selection than variables. Rules were turned into constraints (i.e., mandatory and primary rules) whenever they were essential to the system coherence. For instance, we impose the deactivation (absence) of a component that could not remain activated under certain conditions. For example, in Eden3, the constraint

$$Ld-, Ak- \gg Fd-$$

prevents the activation of the Food variable while it means of production (lands and equipment) are not available in sufficient quantities.

2. Threshold value calibration

Variables in Eden3 are defined by thresholds upon components in the World3 model. Our goal is to qualitatively differentiate large stocks, comparable to components existing abundantly and having a critical effect on other components, from smaller stocks, comparable to a pre-industrial or collapsed state of the examined component. The thresholds were defined to ensure consistency of interpretation across scenarios, using values that remain constant regardless of the different input parameters in World3.

For most variables, we chose thresholds corresponding to their equivalent values in the year 2000 (Table S1, Supplementary Materials). The curves of LtG scenarios presented in their 30-years update (Meadows et al., 2004) are calibrated to intersect the middle of the ordinate axis with a value corresponding to the year 2000. This threshold value is known and allows for practical interpretation, prompting readers to consider whether a component is present in larger or smaller quantities compared to the year 2000 (Fig. 2B).

However, the threshold for two types of variables, namely non-renewable resources and technologies, are not precisely estimated either by Meadows et al. (2004) or by ourselves. Both components are current subjects of intense controversies. Non-renewable resources represent the pool of fossil fuels and other raw materials that are available in the Earth's crust. This amount cannot be precisely estimated (Rockström et al. 2009). We thus defined the threshold of this component as "half of the original amount available", triggering a step after which resources become scarcer and more challenging to extract. Note that this threshold represents a limit that cannot be directly compared to the current state our World.

Technologies are envisioned in LtG as responses to issues such as erosion, pollution and resource depletion. However, the specific quantities and precisions for these technologies do not currently exist. Technical progress, disruption or general purpose technologies are abstract economic concepts despite the undeniable materiality of technologies. (Smith 2006; Acemoglu et al. 2012). Therefore, we chose thresholds for technologies that would ultimately enable them to resolve the related systemic issue, and return the affected components to a desired solved state, which in LtG is similar to the year 2000.

3. Validation

The 2002 version of the LtG report encompasses 11 scenarios, each representing different hypotheses and parameters to capture a wide range of challenges and potential outcomes for humanity. To evaluate the fidelity of Eden3 as a translation of LtG, our criterion for

success is the existence of corresponding qualitative and discrete event scenarios in the computed State Transition Graph (Fig. 3).

We specifically focus on a subset of six synthetic variables that are common to both World3 and Eden3. These variables include human population size, industrial output, non-renewable resources, food production, goods and services production, and persistent pollution. These variables, prominently depicted in World3 scenario graphics, are highly relevant for assessing sustainability and collapse.

By defining thresholds for these variables, we are able to determine, for a given scenario and time period, the subset of system states in the World3 output that share equal values for the six synthetic variables (“+” for presence or above threshold and “-“ for absence or below threshold). This process generates a logical sequence of events within the STG dynamics.

Subsequently, we verify if this sequence is reproduced in the State Transition Graph of Eden3 using a dedicated analyzing tool (Cosme 2022; Thomas et al. 2022). The results indicate that all 11 scenarios are successfully captured by this procedure, providing evidence of the model's alignment with the LtG scenarios, and the exhaustivity of World3 analysis.

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