Journal of Evolutionary Economics (2024) 34:351–374
https://doi.org/10.1007/s00191-024-00866-6

REGUAR ARTICLE

The system dynamics approach for a global evolutionary analysis of sustainable development

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Accepted: 23 June 2024 / Published online: 24 July 2024

Abstract

The challenge of pursuing sustainable development highlights the relevance of the complex mechanisms through which natural and social selection processes affect and are affected by the economic system. Current economic development is unsustainable because it fails to generate long-term systemic compatibility between firms and their natural and social environment. This paper evaluates the issue from an evolutionary perspective by conceptualising unsustainability as the emergence of negative macro-selection effects, arising from both the natural and social domains, and argues for a methodological need for closer integration of system dynamics modelling within the evolutionary field. The Earth4All model is then used to illustrate the complex interactions between economic, social, and natural selection processes. The model results illustrate that the current global development trajectory is strongly unsustainable from both a natural and a social perspective, leading to the emergence of relevant natural and social macro-selection mechanisms, whose systemic interactions bring further complex adverse effects.

Keywords Sustainability · Co-evolution · Systems approach · Macro-selection · Co-selection

JEL Classification Q01 · E14 · E17 · F01

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1 Introduction

Realising global sustainable development is the main challenge of this century (Folke et al. 2016; Sachs 2015). In response, sustainability science, a new and innovative field of research, is becoming increasingly popular with scholars and decision-makers (Clark and Harley 2020; Kajikawa et al. 2014; Kates et al. 2001; Komiyama and Takeuchi 2006). Its analysis includes global interactions between environmental, social, and economic domains in order to identify naturally and socially sustainable development patterns (Barbier 1987; Schoolman et al. 2012). Global sustainable development is a multidimensional, future-oriented, complex, and interdisciplinary topic, including the co-evolution of natural, social, and economic processes (Clark and Harley 2020; Costanza 1996; Foxon et al. 2013; Miller and Morisette 2014).

From an evolutionary economics perspective, unsustainable economic development eventually leads to the emergence of disruptive social and natural reactions operating at the macro level. Evolutionary economics usually focuses on microeconomic selection processes, modelling macro processes as exogenous shocks. However, this paper highlights that the anthropic nature of, and direct relation to, economic development trajectories call for an endogenous analytical approach. Furthermore, the growing relevance of these negative selection effects requires that these reactions be adequately integrated into economic analysis. A possible contribution to the significant methodological challenges posed by this integration is to utilise computational system dynamics models, a set of linked integral equations graphically represented by stock and flow diagrams and simulated by algorithms (Barlas 2007; Fiddaman 2002; Forrester 1958; Sterman 2000), in order to capture and analyse economic, natural, and social selection processes, and, crucially, their co-evolution over time.

This argument is supported by an illustration of the Earth4All model (Collste et al. 2023; Randers and Collste 2023), a simulation model incorporating natural, economic, and social selection processes and their nonlinear interactions built in system dynamics software. The model portrays global development processes from 1980 to 2100 and highlights the approach's potential to understand the selection forces for global sustainable development. The Earth4All model illustrates that, barring significant changes in our development model, the negative natural macro-selection processes and, from the middle of the century, even the social macro-selection processes grow in size over time, supporting each other's negative impact. Furthermore, the systemic adaptive capacity is eroded by the simultaneous natural and social crises in the making.

This paper extends the evolutionary economics literature in three dimensions. First, it strengthens the link between evolutionary economics and sustainability science in a novel way. The strong complementarity of evolutionary economics with ecology (Costanza et al. 1993; Faber and Frenken 2009; van den Bergh 2007) and sustainability (Costanza 1991; Mulder and van den Bergh 2001; Safarzyńska et al. 2012) is well known. Many scholars have borrowed evolutionary tools and concepts for application to sustainability science (Grubb et al.

2015; Nannen et al. 2013; Smith et al. 2010). This paper reverses the flow by applying an instrument commonly associated with sustainability science and the study of social-ecological systems, namely: system dynamics modelling, to the further development of evolutionary economics, thereby contributing to the dialogue between two complementary fields of research (Costantini and Crespi 2013; Chizaryfard et al. 2021; Inigo and Albareda 2019; de Vries 2013; Biggs et al. 2021).

Second, this paper contributes to the evolutionary economics literature on selection processes in three ways. To begin with, in evolutionary economics, a selection process could be sustainable over time only if it is generative, i.e., if it produces new variations in each evolutionary cycle (Hodgson and Knudsen 2006). Using a sustainable development framework, this paper proposes a more stringent definition, arguing that only a generative selection process consistent with durable and favourable social and natural conditions could be truly sustainable over time. Furthermore, while the evolutionary literature already describes several micro-level economic selection processes that operate in a complex, multi-level, and multi-dimensional way (Holm et al. 2016; Schot and Geels 2007; Zinovyeva 2010), this paper proposes an additional set of macro natural and social selection processes jointly operating with the traditional microeconomic selection processes. In addition, natural and social selection processes are often represented as exogenous macro shocks (Galor and Moav 2002; Geels 2010; Gowdy 1992); this paper endogenises these selection processes to be consistent with their causal connection to unsustainable development trajectories.

Third, a new use of the system dynamics modelling approach is suggested for evolutionary studies. This modelling instrument, consistent with the evolutionary economics approach (England 1994; Legasto 1980; Radzicki 2003; Radzicki and Sterman 1994), has already been applied by evolutionary scholars to simulate: the regional innovation system (Fratesi 2010); corporate processes of adaptation to external conditions (Romme et al. 2010; Sterman 2000); entrepreneurial cyclical dynamics (Yun et al. 2018); the evolution of researchers' skills and academic engagement (Dolmans et al. 2021); the relationship between innovation and nature (Niosi 2011; Warr and Ayres 2006); the relationship between sustainable development and human capital investment (Tong et al. 2020); higher education (Faham et al. 2017); and aviation biofuel transition (Kim et al. 2019). This paper further extends the reach of the instrument by demonstrating its relevance for the analysis of endogenous macro-selection effects connected to unsustainable development.

The rest of the paper is organised as follows. Section 2 clarifies the link between the selection processes and sustainable development. Section 3 describes the system dynamics approach and its usefulness in studying selection processes. Section 4 illustrates the Earth4All model and its application to the analysis of macro-selection processes. Section 5 highlights the potential of the approach to understand the selection forces that drive global sustainable development. Section 6 concludes. The Appendix provides an overview of the model.

2 Sustainability and selection

Evolutionary economics highlights the necessity of diversity-creation and selection processes to support long-term economic development (Nelson and Winter 1982; Metcalfe 1994, 1998). Inevitably, evolutionary economists focus primarily on economic selection processes. The most studied economic selection mechanism is the market (Antonelli and Feder 2023; Metcalfe and Ramlogan 2008). Institutions have also been described as selection mechanisms (Bianchi 2019; Consoli and Mina 2009). Both markets and institutions are external to the single firm. In addition, scholars describe two types of selection processes internal to firms: the organisational and hierarchical ones (Geisendorf 2011; Knudsen 2002). All these four significant selection processes operate in the short term, within the economic and institutional domains, affecting the specific firm running afoul of the various mechanisms.

Usually, any other selection process, such as a pandemic or a war, is added to economic analysis as an exogenous macro shock that influences economic development through the mediation of standard (micro)economic selection processes (Bullough et al. 2014; Callegari and Feder 2022; Collier 1999; Liagouras 2017). Selection processes resulting from a natural disaster, such as a flood or fire, are no exception (Safarzyńska et al. 2013; Shepherd and Williams 2019). Environmental catastrophes are often seen as exogenous and random events with relevant consequences on human interactions (Gowdy 1992; Dinger et al. 2020). Scholars have analysed the potential scope of these effects and the resilience of socio-economic systems to the possible recurrence of these adverse shocks in the future (Williams and Shepherd 2018; van der Vegt et al. 2015). However, many of these events are also attributable to the consequences of economic activities, such as pollution or deforestation. Therefore, they are ultimately endogenous to the economy.

Some evolutionary scholars have tried to endogenise these macro-selection processes. For example, according to the cultural group selection literature (Henrich 2004; Safarzyńska and van den Bergh 2010), human genetic selection has led to a preference for individuals with pro-social behaviours within their group (Cordes 2019; van den Bergh and Stagl 2003). This natural and micro-level process has led to a macro-selection process, which operates through culture to reduce behavioural heterogeneity within society and economy (van den Bergh and Gowdy 2009; Waring et al. 2022). Contrary to standard (micro)economic selection processes, the cultural selection process operates at an aggregate social level, above the economic and institutional domains, and has an ancestral origin, with a cumulative mechanism over time. In other words, this literature indirectly shows the way in which natural (genetic), social, and economic domains interact.

Another endogenous macro-selection process is proposed by the 'dystopian Schumpeter meeting Keynes' agent-based model. The model endogenises climate change and green transitions within an economic system with heterogeneous firms (Lamperti et al. 2018, 2020), assuming that technical and technological changes affect climate, and that climate changes affect the economy through both frequent but moderate and rare but intensive negative shocks, generated by a cumulative greenhouse gas emissions mechanism that induces the impact of non-linear climate shocks over time. The model shows that the economic damage wrought by climate change and its consequences is much more significant than neoclassical predictions suggest, highlighting that the environment affects are affected by economic development.

Both these two independent evolutionary fields of research show the relevance of macro-selection processes that operate: (i) above the microeconomic and institutional selection processes and through (ii) co-evolution among economic and social/natural domains, and (iii) a long-term cumulative mechanism. The issue of sustainable development generalises and extends these three results, as many apparently non-economic macro-selection processes are ultimately caused by unsustainable economic development trajectories (Dasgupta 2021; Steffen et al. 2015). In the following, each of these properties (systemic level, co-evolution, and long-term cumulative mechanism) is investigated individually.

Systemic level From sustainability science and ecological economics, the economy operates within society which is in turn embedded in the natural environment (Costanza 1991; Folke et al. 2016; Giddings et al. 2002). This implies that social and natural selection processes can be described as mechanisms which influence the economy from the top down. Combining the sustainability and evolutionary economics perspectives, economic development is sustainable over time when its short-term micro-selection processes produce long-term macro compatibility between the population of firms and their natural and social environments. These selection types, being macro rather than micro and not primarily economic in nature, will not directly contribute to development. Indeed, they can reduce diversity without contributing to economic fitness (Gregory 2022; Basker and Miranda 2018) and destroy potentially favourable mutations (Hamano and Vermeulen 2020; Li et al. 2021).

Co-evolution The sustainable development and social-ecological systems literature highlights that economic, social, and natural processes co-evolve, including selection processes (Levin 1999). The outcomes of this complex and looping co-selection must be analysed together, at both the micro and macro levels (Holling et al. 2002). Moreover, the current literature on sustainable development warns of the unsustainability of current economic trends (Carleton and Hsiang 2016; Carrasco et al. 2017; Costello et al. 2020; Tilman et al. 2017). Think, for example, of a flood brought about by the deforestation of riverbanks or a popular uprising triggered by food price shocks in a context of extreme inequality. These events can destroy many local firms, regardless of their productivity or innovativeness. However, analysing them as exogenous shocks is inappropriate because, ultimately, they depend, at least partially, on the unsustainable socio-economic development trajectory generated by the evolutionary processes at the centre of the analysis.

Long-term cumulative mechanism The natural and social macro-selection processes are generated endogenously as part of economic development, albeit with a significant lag and a qualitatively different set of processes (Levin 1998; Steffen et al.

2018). According to the literature on the Earth System, long-term unsustainability can build-up over time until it is released by adverse feedback effects at the macro level, leading to exogenously caused, systemic selection waves (Armstrong McKay et al. 2022; Lenton et al. 2019). The stochastic and aggregate nature of these selection processes implies that they are inefficient in improving consistency between firms and their environment and substantially reduce firms' heterogeneity (Gregory 2022). Thus, a laissez-faire approach to sustainability is untenable from an evolutionary perspective (van Griethuysen 2002).

The integration of these particular selection processes poses significant methodological challenges. Indeed, the standard economic selection process takes place at the micro level, leading to the development at this scale of suitable instruments of analysis, such as agent-based models. However, the selection processes analysed in this paper are macro and endogenous in nature and with an articulate set of co-selections that induces long-term inconsistencies between the resource demands of populations and their environment. Furthermore, their impact is also primarily motivated by population-level characteristics. As such, an analytical instrument focused on the macro level that is able to integrate multiple, interconnected, and cumulative selection processes among them is necessary. The next section argues that a computational macroscale family of models, called system dynamics models, is an appropriate instrument to perform this analytical task.

3 Modelling endogenous macro-selection processes

System dynamics models are structural, disequilibrium models featuring path-dependency, self-organisation, historical time as opposed to logical time (Georgescu-Roegen 1971), and irreversibility (England 1994). They are characterised by the non-linear interplay of feedback loops, enabling the emergence of complexity (Arthur et al. 2015) and an evolving macro development, whose behaviour is strictly dependent on systemic interactions. The non-linear nature of system dynamics enables such models to simulate what in evolutionary economics is referred to as structural change over time through changes in the relative strength of the feedback loops, governed by stock levels and determining systemic outcomes (Robert et al. 2017). The resulting multiple, potentially unstable equilibria resemble the chaotic paths generated by agent-based evolutionary models (Radzicki and Sterman 1994). Thus, system dynamics models enable unintended consequences to be analysed, possibly leading to undesirable systemic outcomes. This affords decision-makers a more flexible instrument for evaluating policy options (Sterman 2006). However, the emergence of novelty is limited to the macro level, with the underlying mathematical model of causal relations remaining fixed (Merali and Allen 2011).

While the above-mentioned limitation in the ability to capture the emergence of novelty may appear crippling from an evolutionary perspective, it is ultimately shared with agent-based models, which has not prevented the latter from becoming the defining instruments of evolutionary economics. Agent-based models can simulate novel emerging outcomes and trends arising from the interactions of heterogeneously-behaving agents, including elements of stochasticity, leading to a better understanding of innovation-based competition and its systematic consequences (Nelson and Winter 1982). However, behavioural sets, while potentially varied, are necessarily exogenous. Actual agent behaviour can change within the model due to the evolution of environmental variables, but only within the exogenously given set of behavioural patterns and parameters determined ex-ante during the model programming phase. Agent interaction begets emergent novelty, but the underlying behavioural structure remains unchanged. The dynamics of open systems cannot be represented by either system dynamics models (Hayden 2006; Lane 2000) or agent-based models (Guerini and Moneta 2017; Rahmandad and Sterman 2008).

Both agent-based and system dynamics modelling methods comprise: (i) an exogenous component, defining (ii) an open interaction space, which may lead to (iii) the emergence of constrained novelty. For agent-based models, the exogenous component is the behavioural sets of the agents typically involving randomness, as well as the given environmental conditions in which they operate. The interaction space is the endogenous environmental component, whose actual values affect the behaviour of all agents, leading to the emergence of non-linear dynamics as the agents adapt to an ever-changing environment. For system dynamics models, the exogenous component is the system structure given by the designed stocks, their associated initial values, and the functions structuring their flows. The positive and negative feedback loops produce the interaction space that can lead to the emergence of non-linear dynamics and unexpected systemic outcomes. Thus, agent-based models can be described as a micro-modelling approach, starting from single agents' behaviour sets (Pyka and Fagiolo 2007). In contrast, system dynamics models can be described as a macro-modelling approach, typically starting from aggregated stocks and flows representing population-level mechanisms (Hafner et al. 2020), embracing *systemism* rather than the *methodological individualism* (Bunge 2000) of agent-based models.

Both of these modelling approaches are consistent with foundational assumptions of the evolutionary perspective and serve its overall goal: the analysis of novelty emergence, selection, and diffusion. Therefore, both could be useful in the study of macro-selection processes. The previous section has highlighted three distinguishing features of such processes. First, their mechanisms operate at an aggregate, systemic level: the accumulation of imbalances between the aggregate resources demand of all economic activities and the socio-environmental carrying capacity leads to selection effects. Second, their mechanisms encompass the economic, social, and environmental domains, thereby identifying a composite causality structure. Third, they operate with significant lags, as unsustainable development processes are revealed when critical thresholds are surpassed, leading to non-linear responses.

Agent-based models can simulate lags effectively, as the interaction effects between agents can build up their effects through time (e.g., Brouillat 2015; Jacob Leal et al. 2016). However, they cannot be efficiently used in analysing mechanisms operating at the aggregate level (Assenza and Delli Gatti 2013). Finally, while the integration of composite mechanisms could be realised at the micro level through integrating different types of agents, it would come at significant analytical costs. The inclusion of additional heterogeneous populations of agents in the model would increase its complexity, making the identification of causal links between aggregate outcome and micro dynamics unclear at best. Therefore, while an agent-based model could manage composite causality, it would be cumbersome and provide only modest analytical benefits.

The system dynamics models better fit the three features of the analysis of endogenous macro-selection processes. First of all, their systemic nature is tailored for analysing mechanisms operating at the aggregate level. Secondly, since the levels of model stocks are functions of the rates of flows, lags can be easily accommodated; in fact, the analysis of threshold effects is a well-known feature of these models (Weaver and Richardson 2006). Finally, composite causality can be integrated without exceeding complexity due to the aggregate nature of the model variables and the only implicitly assumed micro-level heterogeneity. For this specific analytical need, the lack of micro-level mechanisms (Fallah-Fini et al. 2013) is essential for correctly identifying dominant feedback loops behind the macro-selection mechanisms.

The considerations above lead us to conclude that, if macro-selection processes generated by unsustainable development patterns are included within evolutionary economics, their analysis should be carried out through system dynamics modelling. These considerations do not invalidate but reinforce the need for analysing diversity-creation and micro-selection processes through agent-based modelling. Indeed, system dynamics and agent-based models are complementary (Balint et al. 2017; Swinerd and McNaught 2012; Wu et al. 2010). On the one hand, agent-based models provide the necessary data for validating system dynamics model structures by defining the range of novelty arising from micro-level interactions. On the other hand, by identifying the range of macro-level outcomes arising from such processes, system dynamics models can determine the exogenous environmental conditions of agent-based models, thus helping with their development and validation. Combining agent-based and system dynamics models is one way to overcome the limitations of both. The system dynamics models help agent-based models not to lose the overarching systemic perspective when reconstructing aggregate variables (Assenza and Delli Gatti 2013). Similarly, agent-based models contribute by portraying innovation as a micro process of novelty generation and selection with systemic consequences (Schumpeter 1934).

Theoretically, a composite model can simultaneously simulate the diversity-creation and micro- and macro-selection processes; therefore, it should be considered the better choice to simulate real-world outcomes. However, the composite model is not the superior choice in all cases. Indeed, when the goal is to understand and analyse the different mechanisms separately, a composite model presents two significant problems, which partially explain their relatively limited diffusion (Guerrero et al. 2016). First, a wider variety of mechanisms imply an even wider variety of potential outcomes and a more complex causal tapestry; realism conflicts with analytical clarity. Second, the macro-selection processes will likely lead to a reaction at the micro level. Such a reaction may ameliorate or aggravate the process at hand, but there is a significant risk of this obscuring the macro-selection process.

When exploring the functioning, reach, scope, and potential consequences of mechanisms operating exclusively at the macro level, which is the purpose of this paper, a composite model does not appear to hold any specific advantage over a pure system dynamics model. Indeed, the composite instrument is not only unwieldy, but even inferior for this purpose. Therefore, a purely macro instrument is sufficient to simulate the working, causes and effects of macro-selection processes. While a composite model will eventually be required to analyse realistic interaction effects and produce more reliable future scenarios, an analysis which isolates the macro-selection mechanisms is a necessary preliminary step. To illustrate what kind of data and conclusions to which a system dynamics model of macro-selection effects can contribute, the following section describes an example in this regard called the Earth-4All model (Dixson-Declève et al. 2022; Randers and Collste 2023; Collste et al. 2023). It simulates the complex interactions between economic, social, and natural selection processes and their long-term consequences which affect the development patterns on a global scale.

4 The Earth4All model

The Earth4All model is a model built in system dynamics software which simulates a simplified global socio-economic system and the Earth's biophysical systems combined into one integrated framework, which produces internally consistent scenarios for combining the two systems from 1980 to 2100 (Collste et al. 2023). Earth4All builds on earlier models dating as far back as the 1970s, including World2 (Forrester 1971), World3 (Meadows et al. 1972, 1974), Earth3 (Collste et al. 2021; Randers et al. 2019) and ESMICON (Randers and Golüke 2020; Randers et al. 2016).

Technically, the model is built around differential equations and integrals. The Earth4All model presented in this paper is structured in 11 sections (see Fig. 1). Three sections are social: population, well-being, and public sector; five are economic: inventory, output, demand, finance, and labour market; and three are environmental: energy, climate, and food and land use. Each section encompasses a set of stock (level) and flow (rate) variables, totalling 957 in the model. For example, the output section includes 103 interconnected variables, with GDP being the most central for our analysis here. Moreover, all sections are tightly coupled and receive input and provide output to other sections for every time step. Each time step is 1/64 years. The model has been developed in Vensim and Stella software.

The model is causal-descriptive and hence not only driven by data. Instead, as in the system dynamics practice, the model is primarily endogenously driven. Nevertheless, five primary data sources were used for model calibration between 1980 and 2020: UN population data for total population, fertility rates, and mortality rates (United Nations Population Division 2020); The Penn World Tables for macroeconomic model calibration – including GDP levels, government spending and consumption (Feenstra et al. 2015); BP Statistical Review of World Energy including energy sources and total production; EDGAR for climate-related data, including emissions and emission types; and the World Bank Development Indicators (World Bank 2018). However, given the overarching structure and aim of the model to give an overview of world dynamics, the calibration of the model focused on the replication of key reference modes drawn from real global data patterns and was only semi-automatised. Table 1 clarifies the data used for the main variables in the model.

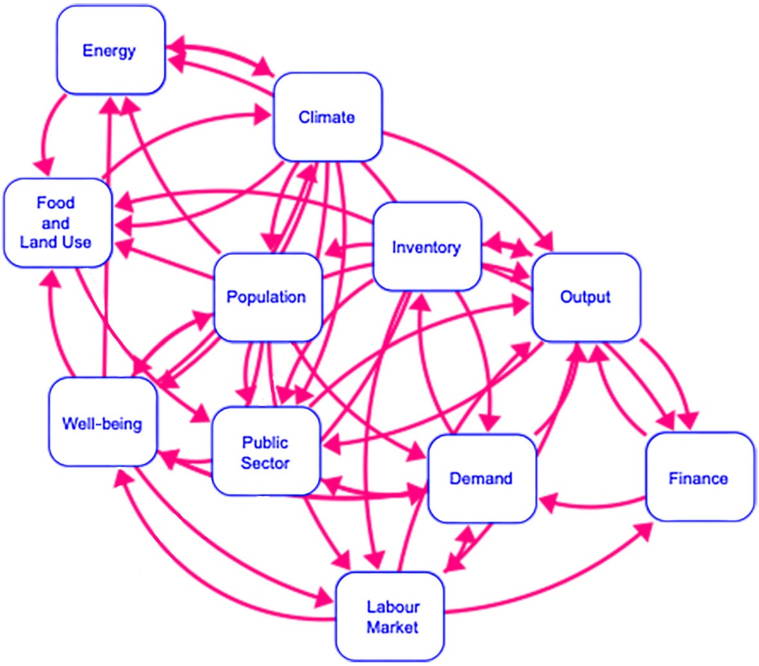

Fig. 1 Earth4All 11 sections and their connections

The start of model simulations in 1980 is a pragmatic choice dictated by data availability and calibration requirements (Randers et al. 2019; Collste et al. 2023). Furthermore, it has been argued that the 1980s mark the onset of today's global 'world system', with a geographically widespread political shift towards laissez-faire capitalist systems (Newell 2013) and increasingly globally interconnected trade and finance (Mol and Spaargaren 2012). Even more important for our analytical goals, the 1980s marked when the human ecological footprint first exceeded the global carrying capacity (Wackernagel et al. 2002).

The model simulates macro-selection processes through direct and indirect reductions in GDP, simulating economic losses generated by natural and social processes which arise in response to unsustainable development trajectories. While each selection process affects specific sectors, regions and/or economic activities, their overall impact is uncorrelated with the respective microeconomic and sustainability performance of the affected areas. For a more in-depth model description, see Collste et al. (2023) and Randers and Collste (2023).

Starting from the Earth4All model modified for this study, the six macro-selection processes are simulated. Figure 2 illustrates the pure macro-selection mechanisms, i.e., without the complex network of indirect and feedback effects that are incorporated in the overall process. Figure 2a and b display the macro-selection processes directly connected to climate change. Figure 2a shows how climate change drives average temperatures higher, leading to a number of adverse effects which affect human life directly and indirectly through the destruction and degradation of

Table 1 Main calibrated variables

Section	Variable	Data source
Climate	Observed global warming	NASA GISS Surface Temperature Analysis (GISTEMP v4)
	CO2 emissions GtCO2/y	EDGAR (EDGAR v6.0 GHG)
Demand	Savings as fraction of GDP	Penn World Table (PWT v10.0)
	Consumption as share of GDP	Penn World Table (PWT v10.0)
	Inequality	World inequality report (wir2022)
Energy	Energy use by source	BP Statistical review of world energy
Food and land use	Forestry land (Mha)	FAOSTAT database (2020)
	Cropland (Mha)	FAOSTAT database (2020)
	Fertilizer use Mt/y	Regionalisation of FAO & Hyde data (v0.1.0)
Labour market	Capital labour ratio	Penn World Table (PWT v10.0)
	Worker share of output	ILO Modelled Estimates (ILOEST database)
Output	GDP	Penn World Table (PWT v10.0)
Population	Population	United Nations World Population Prospects (WPP 2019)
	Fertility	United Nations World Population Prospects (WPP 2019)
	Mortality	United Nations World Population Prospects (WPP 2019)
	Births	United Nations World Population Prospects (WPP 2019)
	Deaths	United Nations World Population Prospects (WPP 2019)
	Life expectancy	United Nations World Population Prospects (WPP 2019)
Public sector	Government spending	Penn World Table (PWT v10.0)
	Government share of GDP	Penn World Table (PWT v10.0)

productive assets (Batten et al. 2020; Diaz and Moore 2017; Newell et al. 2021). The model simulates the process by calculating the increase in temperatures through a simplified climate model, inspired by the ESMICON model (Randers and Golüke 2020; Randers et al. 2016). The increase in temperature negatively affects the life expectancy of installed productive capacity, thus leading to a reduction in GDP, compared with the unconstrained scenario. Figure 2b portrays how environmental degradation in the modified model increases the risks and scope of adverse climate events, precipitating destruction across the globe (Estrada et al. 2019; Kompas et al. 2018) and increasing costs for installing new production capacity, thus negatively affecting GDP growth.

Figure 2c and d shows the natural macro-selection processes mediated by agricultural and energy dynamics, respectively. Figure 2c displays the soil quality and agricultural output degradation due to unsustainable trends in intensive agriculture and global warming (Mäkinen et al. 2018; Tesfaye et al. 2017). A decrease in agricultural yields implies an increase in the cost of capital services, which negatively

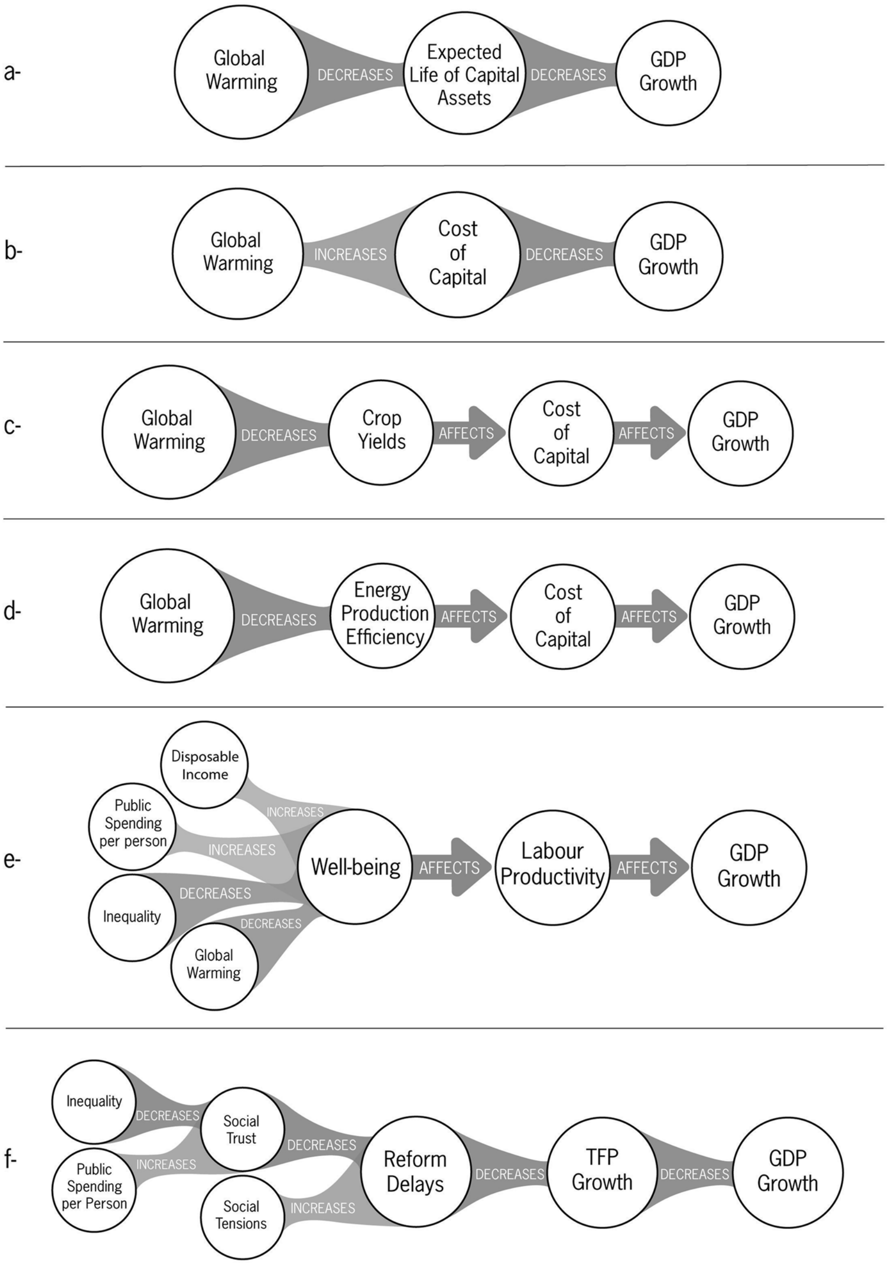

Fig. 2 Macro-selection mechanisms overview

affects long-term GDP growth. Figure 2d illustrates how increasing global temperatures affect economic growth through the degradation of the ability of installed capacity to produce energy (Craig et al. 2018; Tobin et al. 2018; Spalding-Fecher et al. 2016; van Vliet et al. 2016). The reduction in energy production efficiency leads to increasing the cost of energy and, thus, of capital, thereby decreasing the GDP. These effects cover the macro-selection processes arising from the natural domain.

Figure 2e and f describes two macro-selection processes which mainly arise from the social domain. From Fig. 2e, the decrease in social well-being, calculated over average disposable income, public spending per person, inequality, and global warming, decreases the productivity of labour (Bryson et al. 2017; DiMaria et al. 2020), which negatively affects the GDP. Finally, from Fig. 2f, inequality and the decline in public spending per capita decrease social trust (Wilkinson 2002, 2020); this, combined with increased social tensions, reduces the ability to produce reforms (Barr 2016; Patashnik 2019), eventually reducing the growth of the TFP component of GDP (Feng et al. 2021; Martínez-Zarzoso et al. 2019).

The stochastic and cumulative nature of these inconsistent selection processes implies that they diminish both advantageous mutations and heterogeneity of firms (Gregory 2022; Li et al. 2021). From an evolutionary perspective, both elements stifle the dynamism and adaptability of economic systems, limiting their capacity for innovation and resilience over time. Consequently, the adaptive capacity of the economic system, which is crucial for effectively responding to changing conditions, is strongly constrained. For instance, deforestation or extreme inequality could induce a flood or a popular uprising, respectively. These natural or social selection mechanisms can devastate local businesses, irrespective of their productivity or level of innovation. The resulting direct and indirect reduction in firms' diversity is a hindrance to long-term economic development.

All selection processes decrease the GDP, negatively affecting the output. From these dynamics, a complex tapestry of cause-and-effect relationships emerges, impacting all sections of the system dynamics model previously described. The Appendix includes an overall systems diagram that represents these processes, which tries to grasp the circular nature of the macro-selection and their complex consequences.

5 Results

This section presents the simulation results of the six macro-selection processes as follows. Figure 3a illustrates the natural selection effects and their related co-selection effects, while Fig. 3b shows the relative strength of each mechanism. Figure 4a and b does the same for the social mechanisms, their co-selection effects and relative impact. Finally, the total impact of the aggregated natural and social selection processes and the co-selection effects on GDP are depicted in Fig. 5a and b. Each figure is accompanied by our proposed interpretation and consequent methodological implications. Note that the quantitative results presented for the co-selection processes serve methodological and illustrative purposes. Kotz et al. (2024) propose empirical estimates of the macroeconomic effects of climate change, albeit that they are not directly applicable to our analysis.

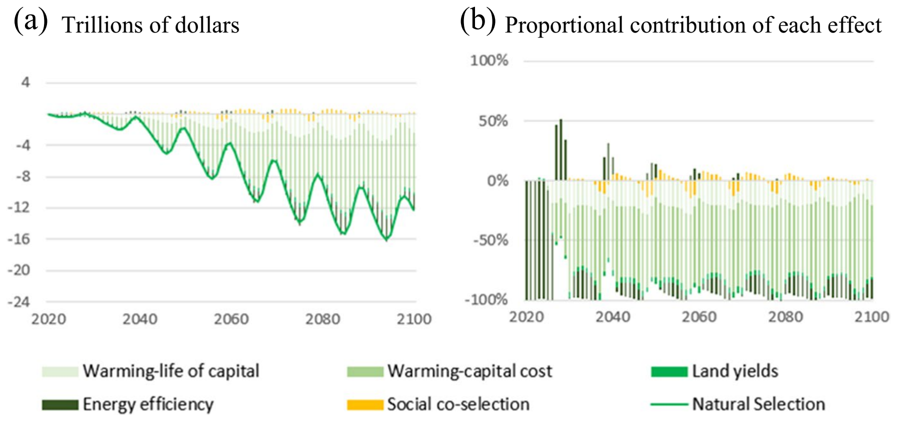

Fig. 3 Impact of natural macro-selection processes on GDP from 2020 to 2100

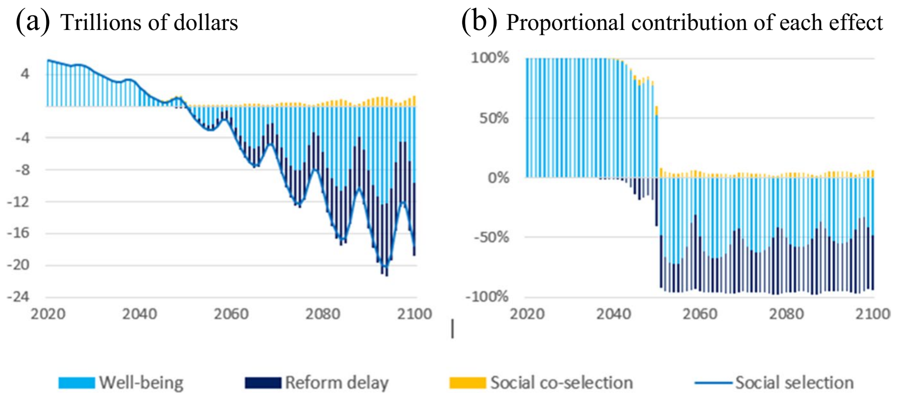

Fig. 4 Impact of social macro-selection processes on GDP from 2020 to 2100

Figure 3 shows the dramatic impact of the unchecked continuation of unsustainable economic development patterns in the model simulation, and the consequent natural selection mechanisms. The cyclical shape of the overall effect is a consequence of the cyclical nature of economic development, with aggregate selection mechanisms waxing and waning in strength in sync with global development waves, with the two mechanisms which depict the direct consequences of global warming on GDP having the strongest negative impact. The energy-based selection mechanism shows a strong cyclical component, heavily influenced by growth patterns. While weakly positive on the initial upswings, the negative impact of climate change on energy productivity eventually turns the selection mechanism purely negative by 2070, while simultaneously increasing its scope. The negative impact of global warming on land yields, while initially negligible, grows during the entire period. While the global impact in the

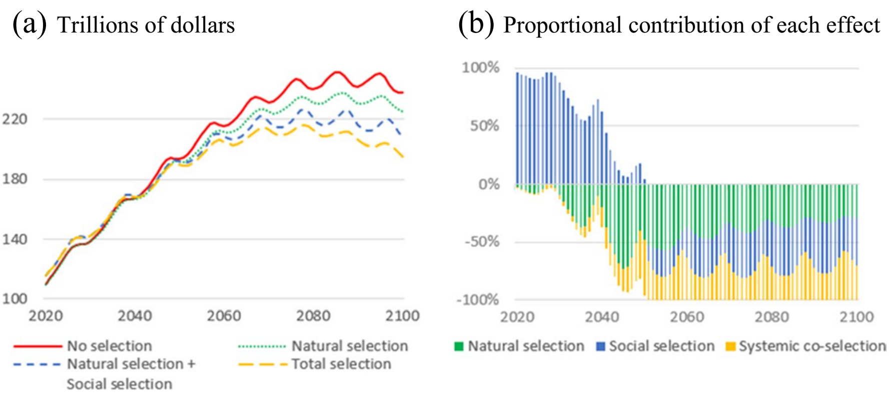

Fig. 5 Overall impact of macro-selection processes on GDP from 2020 to 2100

simulation remains small, its local effects can be significant, especially for low-income countries which face potential food shortages. Finally, the natural co-selection effect, generated by the systemic reaction to the natural selection effects taken into account as a whole, shows a peculiar cyclical pattern, also correlated with global economic performance. During periods of economic expansion, the co-selection mechanism is positive, as a constructive adaptation to changing environmental conditions contributes to global growth. During recessions, however, as the availability of capital suddenly diminishes, the system loses adaptational capability, and the natural co-selection effect turns negative. While the adaptive capacity signalled by the positive upswings does increase over time, such growth ultimately ceases, without succeeding in overturning the negative impact generated by the aggregate natural selection effects. Furthermore, the negative side of co-selection also worsens over time, as the increasingly unsustainable nature of development makes late correction attempts increasingly difficult.

Figure 4 illustrates macro-selection processes arising from the social domain. The well-being effect, initially positive, albeit decreasing, which reflects the impact of continuous economic growth on individuals' welfare, turns negative after 2050, as the simulated effects of climate change become more and more prominent. The situation is worsened by the always negative reform delay effect, which starts affecting the modelled outcomes around 2040, when the insufficient nature of current policy trajectories becomes evident, steadily growing in size and even becoming dominant by the end of the century. Finally, social co-selection effects are purely positive, reflecting the capability of society to adapt gradually to the new normal conditions wrought by continuous climate change. However, they are almost inconsequential in size, an aspect with two non-competing possible explanations. It may be that the limited number of social selection effects featured in the current version of Earth4All, and the accompanying limited integration of the section with the rest of the model, prevent a more significant effect from emerging. However, it may also be the case that the potential of social adaptation to climate change remains limited, as may be suggested by the latter's potentially disruptive and violent nature. Future iterations of this and other system dynamics models should be able to illuminate the issue.

Lastly, Fig. 5 describes the overall impact of natural and social macro-selection processes on GDP over time. The red line in Fig. 5a corresponds to the counterfactual GDP which excludes the highlighted macro-selection processes. The green line includes only the natural macro-selection processes, with the relative co-selection effects described in Fig. 3. The blue line includes both natural and social macro-selection and co-selection processes. By construction, the difference between the green and the blue lines measures the social macro-selection processes described in Fig. 4. Finally, the yellow line provides the overall impact of natural and social macro-selection processes on GDP over time. In this case, the difference between the blue and the yellow lines provides the co-selection effects which arise systemically from the interaction between the natural and social macro-selection mechanisms. In contrast with the natural and social co-selection effects, the total co-selection effects are always negative and steadily growing in size for the entire period of analysis. These results illustrate that, while significant adaptive capabilities to either natural or social crises exist, the interaction of potential future natural and social crises could severely degrade the ability of both firms and decision-makers to react constructively. While deserving close scrutiny, this result provides yet another strong incentive for global leaders, public and private, to act sooner rather than later.

According to these simulations, the negative macro-selection mechanisms have, on the whole, a relatively weak impact on GDP up to the 2040s, hiding their disruptive potential, due to the significantly positive well-being effect. However, from the 2040s onwards, natural macro-selection mechanisms emerge in all their strength, triggering a feedback effect which heightens the destructive impact of all macro-selection mechanisms, with social macro-selection processes reinforcing this negative trend at a later stage. Therefore, the model illustrates that, if unsustainable economic development continues, macro-selection processes could constrain and eventually neuter GDP growth. Furthermore, these macro-selection processes may significantly reduce the variability of business cycles, as their systemic impact appears countercyclical. This further underlines the markedly endogenous nature of these macro-selection effects. Unsustainable economic growth phases heavily impact on the environment and society, leading to the emergence of macro-selection processes that reduce GDP. This effect, compounded by recessions, weakens the macro-selection process, allowing unsustainable economic growth to restart. The results underline the analytical need to switch from an exogenous approach to modelling macro-selection effects to an endogenous one, as their relevance for global development increases.

6 Conclusion

Evolutionary economics mainly studies economic diversity-creation and selection processes at the micro level and relegates selection processes which are not strictly economic to exogenous macro shocks (Gowdy 1992). However, the current unsustainability of the global economic model makes, and will continue to make, these macro-selection processes increasingly relevant (Dasgupta 2021). Therefore, it becomes increasingly crucial to incorporate these processes into evolutionary economics studies and understand their causes and effects. Furthermore, the sustainable development literature describes how the natural (Darwin 1859), social (Malthus 1798), and economic (Nelson and Winter 1982) selection processes co-evolve over time (de Vries 2013). However, the current tools used by evolutionary economics have only a limited capacity to describe these complex and systemic co-selection processes.

This paper proposes the use of system dynamics models (Forrester 1958; Sterman 2000) to analyse the macro-selection processes endogenously. This tool is particularly interesting for evolutionary economists because it is consistent with their theoretical framework (Radzicki 2003) and complementary to the intensively used agent-based models (Balint et al. 2017). The modified Earth4All model provides an illustrative stepping stone towards the analysis of macro-selection mechanisms. While currently muted by productivity-enhancing innovation and the positive consequences of global growth, the model illustrates that, eventually, the unsustainable consequences of the current development trajectory could bring significant and increasing consequences for the well-being of individuals and the wealth of nations.

This paper contributes toward an evolutionary interpretation of sustainability by proposing: a definition of a sustainable economic selection process; an evolutionary conceptualisation of the consequences of natural and social unsustainability; a methodological discussion of suitable instruments of analysis; and an example of how a system dynamics model can be employed in this kind of study. Although the last aspect is the least relevant for the purposes of this article, it is nevertheless the one that can be most improved upon and that may provide significant insights for policymakers.

The next steps of the research will move in this trajectory by expanding the Earth4All model in three primary directions. Firstly, improving the integration of the social variables with the rest of the model would further improve our understanding of social macro-selection processes. Secondly, incorporating a Schumpeterian macroeconomic perspective into the economic components of the system dynamics model would enhance our approach from an evolutionary perspective. Finally, it is now feasible to develop a combined model which incorporates both system dynamics and agent-based models to surmount the respective limitations of each tool, resulting in a more realistic model.

Much remains to be done for the complete integration of evolutionary economics and sustainability science, but the way ahead looks promising. Hopefully, this paper has contributed to highlighting the analytical and practical rewards offered by integrating these fields in order to design better public policies and private strategies for realising a common sustainable future.

Appendix

This appendix provides a more comprehensive description of the Earth4All model. The paper features a modified version of the model originally presented in Dixson-Declève et al. (2022) and documented in Randers and Collste (2023) and Collste et al. (2023).,[1,2]

[1] The original Earth4All model can be downloaded in Vensim or Stella software with links available at: https://stockholmuniversity.app.box.com/s/uh7fjh52pvh7yx1mqfwqcyxdcvegrodf.

[2] A full documentation of the original Earth4All model has also been made available at: https://doi.org/10.5281/zenodo.8230404 and https://worlddynamics.github.io/Earth4All.jl/.

Figure 6 represents the overarching dynamics of the Earth4All model, highlighting the six macro-selection processes within the overall model adapted from Collste et al. (2023). All six mechanisms directly decrease output. This reduction in GDP produces a negative impact on income per person, savings, and investments. These effects impact production capacity, population, and energy. Finally, all elements of the model are indirectly affected by the selection processes, including environmental damage, leading to further selection.

These looping and complex selection effects only partially decrease over time. Indeed, lower output decreases natural selection but increases social selection. In other words, GDP growth is anticyclical in regard to natural selection, and procyclical in regard to social selection. The long and composite cumulative effect of these co-selection processes is overall described in Figs. 3, 4 and 5, where the GDP, calculated without any macro-selection process, is first compared with the GDP with natural selection mechanisms (in green), then with the GDP with only social selection mechanisms (in blue) and finally with the GDP with both macro processes simultaneously present.

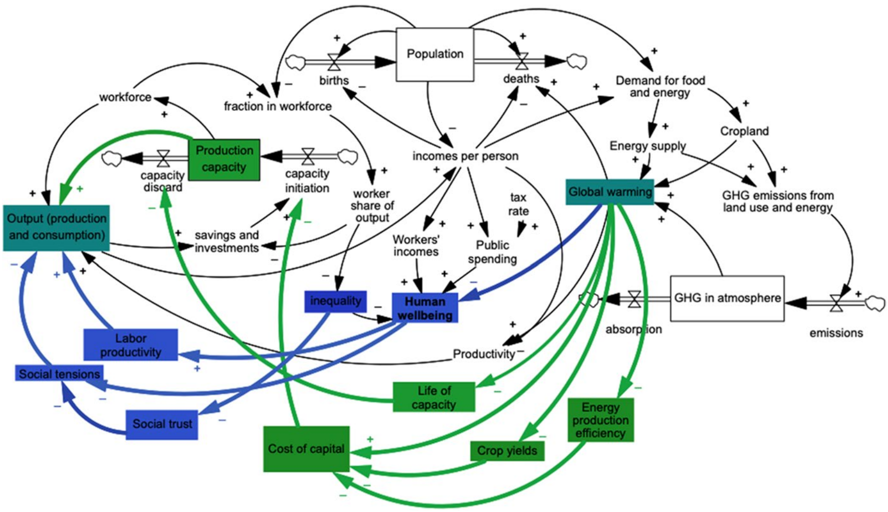

Fig. 6 Macro-selection mechanisms in the overall model. Note: The stocks are represented by boxes, and the flows are represented by pipes and faucets. The + (−) signs next to the arrowheads imply a positive (negative) causal relationship. The relationships and the variables that describe the direct natural and social selection mechanisms are highlighted in green and blue, respectively. The sea green variables are in both selection processes. Source: Our own elaborations from Collste et al. (2023)

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00191-024-00866-6.

Acknowledgements We wish to express our sincere gratitude to our colleagues involved in the Earth4All initiative, with special acknowledgment to Per Espen Stoknes for spearheading the project and contributing significantly to the development of the Earth4All model. Our heartfelt appreciation goes to Jorgen Randers for his leading role in conceptualizing and constructing the Earth4All global model, and to Ulrich Golüke for his contributions to scenario design and narrative development within the model. We also extend our gratitude to the participants of the 19th International Schumpeterian Society Conference and the 63rd Yearly Scientific Meeting of the Italian Economic Association for their valuable feedback on earlier versions of this manuscript. The usual disclaimer applies.

Author contributions All authors contributed to the study conception and design. All modelling tasks were performed by David Collste. The first draft of the manuscript was written by Beniamino Callegari and Christophe Feder, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Kristiania University. College Partial financial support was received from the Club of Rome, as part of the Earth4All project. David Collste was also partially supported by Mistra—the Swedish Foundation for Strategic Environmental Research (DIA 2019/28) and Formas—a Swedish Research Council for Sustainable Development, as part of the national research programme on climate (project number 2021–00416). Christophe Feder was also partially supported by the research project PRIN B53D23010030008.

Data availability The datasets generated and analysed during the current study are not publicly available due the fact that they constitute an extract from research in progress but are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no other relevant financial or non-financial interests to disclose.

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