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ECONOMY AS A COMPLEX ADAPTIVE SYSTEM: AN APPROACH FROM EVOLUTIONARY BIOLOGY

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ABSTRACT

This article aims to analyze ecological economics as a complex adaptive system by integrating principles of evolutionary biology, with the goal of understanding the dynamics of coevolution between socioeconomic and ecological systems under biophysical constraints. A qualitative, theoretical-explanatory methodology is used, based on transdisciplinary literature review and abductive reasoning, drawing on a corpus of specialized scientific literature. The results indicate that economic systems operate through evolutionary mechanisms of variation, selection, and retention, conditioned by nonlinear dynamics, thermodynamic limits, and multiscale interactions. It is concluded that sustainability must be understood as a dynamic co-evolutionary process, which implies moving beyond linear approaches and adopting analytical frameworks grounded in complexity, resilience, and institutional diversity.

Keywords: coevolution, resilience, social metabolism, polycentric governance, sustainability.

INTRODUCTION

The conceptual link between evolutionary biology and ecological economics represents a field of growing interdisciplinary interest, particularly in the context of the challenges associated with socio-environmental sustainability. While evolutionary biology studies the processes that lead to the diversification and adaptation of organisms through mechanisms such as natural selection, genetic drift, and coevolution, ecological economics analyzes the relationship between human activities and the ecological systems that support them, emphasizing biophysical limits and the irreducibility of thermodynamic laws to conventional economic analysis (Andrade-Pérez, 2019; Gómez-Rodríguez, 2024).

Economic systems can be understood as complex adaptive systems that evolve under selective pressures analogous to those acting on biological populations (Hinkelammert and Mora-Jiménez H, 2008). Technological innovation, institutional change, and the transformation of consumption patterns are mediated by variation, selection, and cultural and technological inheritance. This view breaks with the neoclassical premise of general equilibrium and perfect optimization, recognizing the historicity, contingency, and irreversibility of economic processes (Acevedo-Osorio *et al*., 2019; Maldonado, 2023a).

Similarly, ecological economics, by adopting principles from evolutionary biology and systems ecology, recognizes that economic dynamics are subordinate to the flows of matter and energy that traverse ecosystems (Wiedmann *et al*., 2020; Rendón-Acevedo and Gómez-Rodríguez, 2022). Furthermore, the appropriation of ecosystem services, the degradation of natural resources, and the accumulation of waste are understood as inherent components of the economy, whose consequences feed back into evolutionary processes at the social and ecological levels (Martínez-Ramírez *et al*., 2024).

This integrative approach argues that sustainability is not a static state, but rather an evolutionary process of co-adaptation between socioeconomic systems and ecosystems. From this perspective, concepts such as resilience, functional diversity, and adaptive capacity are key to understanding human development within planetary boundaries. Consequently, ecological economics must incorporate the principles of evolutionary biology not merely as explanatory metaphors but as rigorous theoretical foundations that enable us to describe, interpret, and guide the evolution of economic systems toward configurations more compatible with life on Earth (González-de Molina *et al*., 2020; Carrizosa *et al*., 2023).

In this context, this article explores how the principles of evolutionary biology can be integrated as analytical mechanisms, and not merely as heuristic analogies, within the framework of ecological economics to explain the co-evolutionary dynamics of socio-ecological systems under conditions of complexity and biophysical constraints (Schramski *et al*., 2015; Ripple *et al*., 2019). To ensure methodological coherence between the research question and the analytical process, the following categories were defined as units of analysis: those derived from evolutionary biology (variation, selection, and retention) and those from ecological economics (social metabolism, biophysical limits, and resilience). These categories guided the construction of the documentary corpus and the subsequent thematic coding. This operationalization translates the research question into a systematic analytical process, ensuring traceability between the problem posed and the results obtained (Maldonado, 2016).

The theoretical gap that justifies this research lies in the absence of a systematic analytical framework that allows us to move beyond the merely metaphorical use of evolutionary biology principles in economic analysis and instead advance toward their incorporation as rigorous explanatory foundations in the study of socio-ecological systems. Despite developments in ecological economics regarding biophysical limits and thermodynamic irreversibility (Georgescu-Roegen, 1994; Martínez-Alier, 2011), a conceptual fragmentation persists that hinders the operational articulation of these principles with the mechanisms of variation, selection, and retention (Maldonado, 2023a, 2023b).

The primary objective of this study is to analyze ecological economics as a complex adaptive system. This analysis is conducted through the theoretical and methodological integration of evolutionary principles. The goal is to construct an interpretive framework that explains the dynamics of coevolution between social and ecological systems, particularly under conditions of complexity, nonlinearity, and indeterminacy (Norström *et al*., 2020).

MATERIALS AND METHODS

This study adopts a qualitative, theoretical-explanatory approach, grounded in a transdisciplinary framework and the abductive logic of knowledge construction. The research aims at the systematic integration of principles of evolutionary biology into the theoretical and analytical framework of ecological economics, with the goal of reinterpreting economic systems as complex adaptive systems subject to biophysical constraints and co-evolutionary processes (Páramo, 2008; Maldonado, 2016).

Similarly, this research project is grounded in the interpretive-complex approach, in which knowledge is not conceived as an objective representation of reality, but rather as a theoretical construct that emerges from the interaction between the researcher and the analyzed corpus. In this sense, abductive logic allows for the generation of plausible inferences that link theory and documentary evidence, consistent with contemporary approaches to research in complex systems (Maldonado, 2016). This epistemological stance is relevant to the study of socio-ecological systems, characterized by nonlinearity, indeterminacy, and multiscalarity (Maldonado, 2023b).

The process of defining the documentary corpus was structured according to explicit inclusion and exclusion criteria, designed to ensure the epistemological consistency and analytical relevance of the selected sources. Documents published primarily between 2000 and 2024 were considered and indexed in high-impact databases such as Scopus and Web of Science, which characterize the dialogues between evolutionary biology, ecological economics, and complex systems theory (Negou *et al*., 2023). The final corpus consisted of a set of approximately 46 documents, selected based on criteria of theoretical saturation and conceptual density, in accordance with integrative review approaches in complex social sciences (Maldonado, 2023b).

The methodological strategy consisted of an intensive literature review, grounded in hermeneutic criticism and structural analysis of specialized academic discourse. A textual corpus was constructed comprising high-impact scientific literature, selected through deliberate theoretical sampling in databases such as Google Scholar, Scopus, Web of Science, and indexed journal repositories. The inclusion criteria prioritized texts with a high citation count, conceptual relevance, and disciplinary representativeness in evolutionary biology, systems ecology, institutional economics, and ecological economics. Likewise, search equations derived from the analytical categories were used from a bibliometric perspective (López-Rodríguez *et al*., 2025).

The analytical strategy adopted corresponds to an abductive approach to structured thematic synthesis, in which analytical categories derived from evolutionary biology (variation, selection, and inheritance) were compared with concepts specific to ecological economics (social metabolism, entropy, and planetary boundaries), allowing for the emergence of interpretive patterns that bridge both fields (Georgescu-Roegen, 1994). This procedure ensures traceability between the documentary evidence and the theoretical construction, strengthening the epistemic validity of the analysis (Maldonado, 2023b; Ali *et al*., 2024) (Table 1).

Table 1. Interdependent methodological levels of the analytical process and their operationalization in the integration of evolutionary biology and ecological economics (Gómez-Rodríguez 2025a, 2025b; Gómez-Rodríguez and Barbosa-Pérez, 2024; Maldonado 2014a, 2014b).

Levels
Deductive category level Analytical categories were proposed based on the classical evolutionary principles of variation, selection, inheritance, coevolution, and resilience, as well as fundamental concepts from ecological economics such as social metabolism, irreversibility, entropy, and planetary boundaries.
Inductive coding level An open and axial coding approach was applied to the documentary corpus, allowing for the emergence of intermediate categories such as "pathways of institutional adaptation," "economic ecosystems," and "evolutionary feedback," which facilitated the connection between the biological and economic levels.
Integrative-systemic level Semantic matrices were designed to link categories across disciplines, based on a socio-ecological coevolution model. This phase made it possible to establish interpretive relationships between adaptive processes in natural systems and their analogues in economically organized human systems.

In terms of methodological rigor, the study adopted quality criteria typical of qualitative research, such as internal consistency, theoretical saturation, and interpretive validity. Consistency was ensured through alignment between the research objectives, analytical categories, and results (Table 2). Theoretical saturation was achieved when the analytical categories no longer generated new interpretive patterns in the documentary corpus. Validity was strengthened through interdisciplinary theoretical triangulation, integrating contributions from ecological economics, evolutionary biology, and complex systems theory (Norström *et al*., 2020; Ali *et al*., 2024).

Furthermore, to enhance the epistemic validity of the analysis, an interdisciplinary theoretical triangulation was used, incorporating concepts from ecological thermodynamics (Georgescu-Roegen, 1994, 1996), evolutionary institutional

Table 2. Relationship between the general objective, analytical categories, and emerging categories within the study's interpretive framework.

Overall objective	Analytical categories	Emerging categories
To analyze the ecological economy as a complex adaptive system, integrating the principles of evolutionary biology to understand the dynamics between socioeconomic systems and ecosystems, with the aim of proposing models that promote sustainability and mutual adaptation.	Evolutionary biology Ecological economics	Evolutionary principles in economic systems. Ecological economics as a complex adaptive system. Coevolution of social and ecological systems. Implications for environmental policy and management.

economics (Norgaard, 1994), the theory of complex adaptive systems (Holling *et al*., 2002), and the planetary boundaries framework (Rockström *et al*., 2009). This triangulation increased the analytical depth of the study and enabled the construction of a robust interpretive framework, sensitive to the complexity and nonlinearity of contemporary socio-ecological dynamics (Costanza *et al*., 2017).

Given the theoretical-explanatory nature of this study, no hypotheses are formulated in the positivist sense; instead, analytical propositions derived from the process of conceptual integration are developed, in line with evolutionary and institutional economic approaches that prioritize the explanation of dynamic processes over statistical verification (Norgaard, 1994; Arias-Prada and Maldonado, 2025). Similarly, each of the theoretical propositions derived in the results section is grounded in patterns of recurrence identified in the documentary corpus through the process of abductive coding, ensuring correspondence between the empirical documentary evidence and the conceptual framework. This procedure avoids speculative inferences and strengthens the interpretive validity of the study within the framework of complex systems theory (Costanza *et al*., 2017; Gómez-Rodríguez, 2025c).

Based on this methodological design, the analysis identified recurring patterns and conceptual relationships among the defined categories, leading to the formulation of theoretical propositions. These propositions are the result of an abductive process of conceptual integration and represent interpretive frameworks that explain the co-evolutionary dynamics between socioeconomic and ecological systems (Leff, 2004b; Maldonado and Concha, 2022).

RESULTS AND DISCUSSION

The results presented below are derived from the systematization of analytical and emerging categories identified in the documentary corpus (46) through a process of abductive coding and interdisciplinary theoretical triangulation. Each proposition corresponds to recurring patterns identified in the analyzed literature, which ensures its epistemological consistency and its grounding in robust conceptual evidence (Maldonado, 2014a, 2014b).

Based on the documentary analysis, a set of theoretical propositions was derived that synthesize the integration of the principles of evolutionary biology and ecological economics, allowing economic systems to be reinterpreted as complex adaptive systems. These propositions emerge from the interplay between analytical categories and conceptual evidence drawn from the documentary corpus, in line with complex systems approaches (Bennett *et al*., 2015; Gómez-Rodríguez, 2025b).

Proposition 1

Economic systems function as evolutionary systems characterized by processes of variation, selection, and institutional retention, whose dynamics are shaped by biophysical constraints and specific socio-historical contexts (Georgescu-Roegen, 1994).

Economic systems can be reinterpreted as dynamic systems subject to evolutionary principles analogous to those observed in biological systems. From a Darwinian perspective, markets exhibit processes of variation (technological innovation, productive diversification), selection (competition among firms, consumer preferences), and retention (institutions, organizational routines), which determine their historical trajectory (Passet, 1996). The theory of economic evolution posits that firms do not optimize statically but rather follow routines analogous to genes that replicate or disappear depending on their adaptation to the competitive environment (Georgescu-Roegen, 1994, 1996).

This framework explains phenomena such as the emergence of monopolies (selection of dominant traits) or the resilience of informal economies (adaptive strategies in marginal niches). Cultural transmission adds a layer of complexity: social norms such as trust or reciprocity act as "memes" that co-evolve with market structures, influencing collective efficiency (Boyd and Richerson, 2005; Giraldo, 2018). Likewise, institutional drift (equivalent to genetic drift) can lead to the entrenchment of suboptimal practices, such as fossil fuel subsidies, due to path dependence. These principles suggest that economic policies should promote institutional diversity and controlled experimentation to avoid technological deadlocks (Gudynas, 2021; Gómez-Rodríguez and Barbosa-Pérez, 2024).

Proposition 2

Ecological economics can be conceptualized as a complex adaptive system in which properties such as resilience, self-organization, and nonlinearity emerge from the interaction between social and ecological subsystems (O'Dwyer and Unerman, 2020; Folke *et al*., 2021).

Ecological economics incorporates concepts from complex systems theory to analyze the interactions between socioeconomic and ecological systems. These systems exhibit emergent properties, such as the self-organization of local markets for common-pool resources or tipping points in climate systems (Ostrom, 2009; Hickel *et al*., 2022). Resilience, defined as the capacity to absorb disturbances while maintaining essential functions, depends critically on functional diversity, such as the plurality of energy sources, and institutional redundancy (Leff, 2004a; Hale *et al*., 2019).

One example is fisheries management: agent-based models (ABMs) show that adaptive rules, such as dynamic quotas adjusted based on biomonitoring, replicate negative feedback mechanisms observed in natural ecosystems (Andrade-Pérez, 2019). Economic thermodynamics (Georgescu-Roegen, 1994) adds a biophysical dimension to the argument: entropic irreversibility imposes limits on the sustainability of extractive patterns, analogous to metabolic costs in ecology (Purvis *et al*., 2018). Likewise, the indeterminacy in these systems requires polycentric governance frameworks where multiple actors, such as the state, communities, and the sciences, co-produce knowledge to manage trade-offs. The analogy with food webs is clear: modularity reduces systemic risks, while excessive connectivity or hyperconnectivity can propagate crises (Martínez-Alier, 2011; Román-Acosta *et al*., 2025).

Proposition 3

Socio-ecological coevolution is a dynamic process of feedback between human and natural systems, mediated by cultural, technological, and institutional mechanisms that operate across multiple timescales (Herrmann-Pillath, 2023; Gómez-Rodríguez, 2026).

Socio-ecological coevolution describes a process in which cultures, technologies, and ecosystems influence one another. A case in point is the domestication of plants: human practices have modified genotypes (teosinte-maize), enabling higher population densities, which in turn have fueled social complexity (Ríos-Osorio *et al*., 2005). In contrast, the Industrial Revolution generated a pathological coevolution: dependence on fossil fuels altered biogeochemical cycles such as that of atmospheric CO_2, exacerbating socioeconomic vulnerabilities (Rauchecker and Chan, 2016; Correa, 2020).

The theory of multilevel cultural coevolution explains how prosocial norms, such as fishing taboos in Polynesia, emerge as group adaptations to ecological constraints (Henrich, 2004). However, globalization has disrupted this coevolution: short-term economic institutions operate on time scales that are incompatible with ecosystem regeneration. Solutions based on coevolution include circular bioeconomies, such as industrial symbiosis inspired by food webs. and the recognition of the rights of nature, as in Ecuador's 2008 Constitution, which reintegrates evolutionary feedback loops into governance. These approaches recognize that sustainability is a dynamic coevolutionary process (Maldonado, 2025b).

Proposition 4

Environmental policymaking must incorporate evolutionary principles and complexity-based approaches, with a focus on adaptive management, institutional diversity, and polycentric governance (Cavender-Bares *et al*., 2022; IPBES, 2022).

The dialogue between ecological economics and evolutionary biology suggests that environmental policies should adopt an adaptive management approach, analogous to phenotypic plasticity in organisms (Williams and Brown, 2016). This involves designing flexible instruments, such as adjustable carbon taxes that respond to real-time ecological signals like biodiversity indices, thereby avoiding institutional rigidities such as the Paris Agreement, where groups with pro-environmental norms gain collective advantages (Bowles and Gintis, 2011).

Panarchy theory proposes that socio-ecological systems go through cycles of growth, maintenance, collapse, and reorganization (Holling *et al*., 2002). In particular, policies can promote controlled transitions, such as the energy transition, to avoid abrupt collapses (Andrade-Pérez, 2019). Institutional biomimicry offers tools such as fishing permit markets that replicate territoriality systems in marine species, while community seed banks emulate seed banks in natural ecosystems (Maldonado, 2025a, 2025b). Finally, the evolutionary uncertainty associated with environmental variability calls for a diversification of strategies, such as agroecology and precision agriculture, to strengthen social learning capacities. This includes crop rotation and the use of resilience modeling tools.

Theoretical convergence and the limitations of the approach

The propositions derived from the literature review reveal a theoretical convergence between evolutionary biology and ecological economics, in that both disciplines recognize dynamic systems characterized by adaptive processes, nonlinearity, and structural interdependence. This convergence allows for a reinterpretation of economic systems within an expanded evolutionary framework, in which institutions, technologies, and social practices are configured as units subject to processes of selection and retention, conditioned by biophysical constraints (Georgescu-Roegen, 1994; Rockström *et al*., 2009).

The proposed conceptual framework is based on the recognition that biological and socioeconomic systems share characteristics typical of complex adaptive systems (Maldonado, 2023a, 2023b). This convergence allows for the analysis of economic processes from a dynamic and evolutionary perspective, where institutions, technologies, and social practices can be understood as units subject to variation, selection, and retention (Sachs *et al*., 2020). However, the methodological challenge remains of translating these theoretical frameworks into operational tools that allow for their empirical application in specific contexts. From this perspective, future research could integrate mixed methodologies, including agent-based modeling and complex network analysis, as well as neural networks, to validate the proposed co-evolutionary dynamics (Díaz *et al*., 2020), advancing from the explanatory to the predictive level in the study of socio-ecological systems.

From a critical perspective, while this integration offers a robust analytical framework, it has limitations stemming from the difficulty of operationalizing evolutionary principles in complex socioeconomic systems. Institutional heterogeneity, multiscalarity, and radical indeterminacy make it difficult to formulate predictive models, requiring hybrid methodological approaches that combine qualitative analysis, agent-based modeling, and dynamic simulations (Díaz *et al*., 2020).

The application of evolutionary principles to economic systems reveals parallels with the processes of natural selection (Hodgson and Knudsen, 2010; Zarta-Ávila, 2018). However, ecological economics introduces a critical dimension by incorporating thermodynamic constraints (Georgescu-Roegen, 1991, 1994) and biophysical limits (Rockström *et al*., 2009) into the analysis of the "fitness" of economic practices. This integration is key to understanding the coevolution between social and ecological systems, where human institutions and ecosystem processes influence one another through complex feedback loops (Ostrom, 2009; Bowles and Gintis, 2011).

However, it is necessary to define the scope of this integration, avoiding simplistic extrapolations between biological and economic systems. The distinction between heuristic analogy and explanatory mechanism is fundamental to preserving the epistemological validity of the approach, especially in contexts where socio-ecological complexity demands interpretive frameworks that acknowledge contingency, historicity, and human agency (Martínez-Alier, 2011; Diesendorf *et al*., 2024). Likewise, the analogy between biological and economic systems does not imply ontological equivalence, so its use must remain within rigorous epistemological limits (Georgescu-Roegen, 1994; Escobar, 2011). By incorporating biophysical constraints and thermodynamic principles, ecological economics introduces a material and normative dimension that transcends evolutionary reductionism and reinforces the need for integrative and transdisciplinary approaches (Martínez-Alier, 2011; Gómez-Rodríguez, 2025a).

CONCLUSIONS

The integration of evolutionary biology and ecological economics allows for a reinterpretation of socioeconomic systems as complex adaptive systems. These systems are characterized by coevolutionary dynamics, nonlinearity, and biophysical constraints. Rather than representing a state of equilibrium, sustainability is understood as a dynamic process of adaptation between social and ecological systems. The mechanisms of variation, selection, and retention provide a relevant analytical framework for understanding the institutional, technological, and cultural transformations that shape the resilience of socio-ecological systems. Similarly, it confirms that functional diversity, adaptive governance, and the capacity for collective learning are central to addressing scenarios of uncertainty and systemic crises.

The main contribution of this article lies in the development of a transdisciplinary interpretive framework that moves beyond the metaphorical use of evolutionary principles and incorporates them as explanatory foundations for the analysis of ecological economics. Consequently, it emphasizes the necessity to move toward operational models and applied methodologies that enable the empirical analysis of co-evolutionary dynamics in specific territorial contexts.

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