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Inteligência Sistêmica. Um Conceito Baseado em Fluxos Energéticos para Ecossistemas Auto-Organizados e Sistemas Socioecológicos Sustentáveis

Systemic Intelligence. A Concept Grounded in Energy Flows for Self-Organizing Ecosystems and Sustainable Socio-Ecological Systems

Inteligencia Sistémica. Un concepto fundamentado en flujos energéticos para ecosistemas auto-organizados y sistemas socioecológicos sostenibles

Alesandra Bez Birolo[1]
Oldemar de Oliveira Carvalho-Junior[2]

[1] Programa de Pós-Graduação em Energia e Sustentabilidade (PPGES), Laboratório de Energias Renováveis e Aceitação Social Institucional, Universidade Federal de Santa Catarina, Brasil
[2] Laboratory for Ecosystem Energy Modeling, Instituto Ekko Brasil, Florianópolis, SC, Brasil

Correspondência para: ocjunior@ekkobrasil.org.br

Resumo: A inteligência é tradicionalmente associada a sistemas cognitivos centralizados, como cérebros ou algoritmos artificiais. Contudo, ecossistemas exibem adaptação, autorregulação e resiliência, indicando uma forma distinta de inteligência: não cognitiva, distribuída e fundamentada em fluxos transformados de energia-matéria. Propomos a Inteligência Sistêmica (IS) como a capacidade sistêmica de ecossistemas e sistemas socioecológicos de perceber, integrar e responder adaptativamente às mudanças, com base em princípios quantificáveis da teoria

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da emergia: transformidade, densidade de emergia, razão de retroalimentação e eficiência no uso de energia de alta qualidade. Ancorada na ecologia de sistemas (H.T. Odum), teoria da complexidade (Holling, Kauffman) e ecologia evolutiva, a IS transcende a cognição individual, emergindo de redes biótico-abióticas que otimizam a persistência por meio da seleção de rotas energéticas eficientes. Reinterpretando processos ecológicos como redes de emergia, análogas a redes neurais, ilustramos como a natureza processa informação ambiental via hierarquias energéticas. Apresentamos como definição operacional e métrica preliminar o Índice de Inteligência Sistêmica (IIS), derivado de indicadores emergéticos. Aplicações abrangem conservação, design regenerativo, governança adaptativa e modelagem de sistemas complexos. A IS oferece arcabouço materialista e mensurável para integrar ecologia, termodinâmica e ciência dos sistemas, rumo a uma ciência da sabedoria sistêmica da natureza.

Palavras-chave: emergia; resiliência sistêmica; teoria de sistemas; índice de inteligência sistêmica

Abstract: Intelligence is traditionally associated with centralized cognitive systems, such as brains or artificial algorithms. Yet, ecosystems exhibit adaptation, self-regulation, and resilience, suggesting a distinct, non-cognitive, distributed intelligence rooted in transformed energy-matter flows. We propose Systemic Intelligence (SI) as the systemic capacity of ecosystems and socio-ecological systems to perceive, integrate, and adaptively respond to change, grounded in quantifiable principles of emergy theory: transformity, emergy density, feedback ratio, and efficiency of high-quality energy use. Anchored in systems ecology (H.T. Odum), complexity theory (Holling, Kauffman), and evolutionary ecology, SI transcends individual cognition, emerging from interconnected biotic-abiotic networks that optimize persistence through efficient energy pathway selection. By reinterpreting ecological processes as "emergy networks", analogous to neural networks, we illustrate how nature processes environmental information via energetic hierarchies. We present an operational definition and a preliminary metric: the Index of Systemic Intelligence (IIS), derived from emergy indicators. Applications span conservation, regenerative design, adaptive governance, and complex systems modeling. SI offers a materialist, measurable framework integrating ecology, thermodynamics, and systems science, moving us toward a science of nature's systemic wisdom.

Keywords: emergy; systemic resilience; systems theory; systemic intelligence index (IIS)

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Resumen: La inteligencia se asocia tradicionalmente con sistemas cognitivos centralizados, como cerebros o algoritmos. Sin embargo, los ecosistemas muestran adaptación, autorregulación y resiliencia, revelando una inteligencia no cognitiva, distribuida y fundamentada en flujos transformados de energía-materia. Proponemos la Inteligencia Sistémica (IS) como la capacidad de sistemas ecológicos y socioecológicos para percibir, integrar y responder adaptativamente a cambios, basada en principios cuantificables de la teoría de la emergía: transformidad, densidad de emergía, razón de retroalimentación y eficiencia en el uso de energía de alta calidad. Anclada en la ecología de sistemas (H.T. Odum), la teoría de la complejidad (Holling, Kauffman) y la ecología evolutiva, la IS emerge de redes biótico-abióticas que optimizan la persistencia mediante rutas energéticas eficientes. Reinterpretando los procesos ecológicos como "redes de emergía" —análogas a redes neuronales—, mostramos cómo la naturaleza procesa información ambiental mediante jerarquías energéticas. Presentamos el Índice de Inteligencia Sistémica (IIS) como métrica operacional derivada de indicadores emergéticos, aplicable a conservación, diseño regenerativo, gobernanza adaptativa y modelización de sistemas complejos, ofreciendo un marco materialista y medible para una ciencia de la sabiduría sistémica de la naturaleza.

Palabras clave: emergía; resiliencia sistémica; teoría de sistemas; índice de inteligencia sistémica

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1 Introduction

The contemporary socio-environmental crisis reveals not only technical or political limitations but also a profound conceptual failure. The enduring dichotomy between intelligence, understood as the exclusive property of brains or algorithms, and nature, treated as inert matter or a predictable machine, must be overcome. While artificial intelligence (AI) systems advance in simulating perception, learning, and decision-making, ecological processes have been operating for billions of years with a distinct form of systemic intelligence: non-cognitive, distributed, and materially grounded in transformed energy flows.

This intelligence does not reside in a central command, but emerges from the dynamics of interconnected biotic and abiotic networks that, over time, select energetically efficient pathways to persist, reproduce, and reconfigure in the face of disturbances. Its physical basis is not digital information, but emergy (embodied energy), the available energy of prior quality, directly or indirectly required to produce a good, service, or structure (Odum, 1996). Thus, emergy does not merely quantify how much energy was used, but what kind of energy, at what hierarchical quality level, and with what efficiency it was incorporated, thereby revealing a capacity for information processing through energetic organization.

In response, we propose replacing the metaphors of nature as a machine (Descartes) or as an organism (Haeckel) with a third alternative: nature as an emergy-based intelligent system, echoing recent calls to view ecosystems not as resources to be exploited, but as partners in co-producing resilience and well-being (Carvalho Junior, 2025). Drawing inspiration from H.T. Odum's systems ecology—not only its structural strand (E.P. Odum)—we introduce the concept of Systemic Intelligence (SI) as:
the systemic capacity of ecosystems and socio-ecological systems to perceive, integrate, and adaptively respond to environmental change through the efficient allocation of emergy, self-regulation via feedback, and hierarchical optimization of energy flows.

E. P. Odum's foundational work emphasized ecosystem structure and functional stability (Odum, 1971), whereas H.T. Odum shifted the focus toward the quality, hierarchy, and informational content of energy flows (Odum, 1996). Our concept of SI builds on the latter, thermodynamically explicit tradition. This concept transcends anthropocentrism without falling into anthropomorphism. It does not attribute "thought" to the forest, but recognizes that its structure (e.g., aerial roots, exclusion zones, closed-loop nutrient cycling) results from a systemic learning process mediated by thermodynamic selection, functionally analogous (though not ontologically equivalent) to the training of a neural network.

The objectives of this paper are to: (i) operationally define Systemic Intelligence using measurable emergy-based indicators; (ii) theoretically ground it in systems ecology, biological thermodynamics, and complexity theory; (iii) establish a functional, non-metaphorical, analogy with artificial neural networks, reinterpreted as emergy networks; and (iv) discuss its implications for conservation, regenerative design, and adaptive governance. By reframing intelligence as energetically embodied, not merely neurally encoded, Systemic Intelligence paves the way toward a more integrated science, where ecology, engineering, and systems science converge around a unifying principle: nature's wisdom is written in transformed joules.

Systemic Intelligence (SI) is defined as *the emergent capacity of ecosystems and socio-ecological systems to perceive, integrate, and adaptively respond to change through the efficient allocation of transformed energy, self-regulation via internal feedbacks, and hierarchical optimization of energy flows*. SI does not require cognition; it arises from the thermodynamic selection of energetically efficient pathways over time and is quantifiable through emergy-based indicators such as transformity, feedback-to-input ratio, emergy density, and emergy efficiency.

2 Theoretical Foundations

The proposal of Systemic Intelligence (SI) does not arise from a metaphorical analogy, but from a convergence among biological thermodynamics, general systems theory, and quantitative ecology, with H.T. Odum as the central figure. While classical ecology (e.g., E. P. Odum, Ricklefs) emphasizes structure and function, energetic systems ecology seeks to quantify nature's work, revealing that ecological systems do not merely function, but learn, store memory, and optimize through the hierarchical incorporation of transformed energy.

While classical ecology emphasizes energy flow and trophic efficiency within bounded systems (Begon; Townsend; Harper, 2006), systems ecology extends this view by quantifying the quality and hierarchy of transformed energy (Odum, 1996), enabling a shift from descriptive to predictive understanding of systemic persistence. Below, we present the four theoretical pillars that underpin SI. Below, we present the four theoretical pillars that underpin SI.

2.1 H. T. Odum's Energetic Systems Ecology: emergy as the basis of ecological information

Howard T. Odum (1924–2002) developed a radically systemic approach to ecology, grounded in the Second Law of Thermodynamics and driven by the search for a common unit capable of comparing biotic and abiotic flows: emergy (embodied energy), expressed in solar emjoules (seJ) (Odum, 1988; Odum, 1996). For Odum, biological information is embodied energy, and ecological complexity emerges from the long-term selection of the most energetically efficient pathways.

Odum's rejection of the notion that energy is equivalent to joules was of paramount importance. Instead, he argued that energy quality, measured by transformity (transformity = seJ/J), is what confers organizational power to a system. One joule of fish biomass has far higher transformity than one joule of solar radiation, as it incorporates multiple transformation steps (photosynthesis $\rightarrow$ phytoplankton $\rightarrow$ zooplankton $\rightarrow$ fish). This energetic hierarchy effectively constitutes an information-processing network. The higher the transformity of a component, the greater its systemic decision-making capacity (e.g., top predators regulate flows across the entire trophic network).

Odum went further. He proposed that systems with a high feedback-to-input ratio (*F/B*), where *F* (feedback) represents internally recycled emergy (e.g., from decomposition, excretion, or nutrient cycling) and *B* (boundary input), denotes emergy entering the system from external sources (e.g., sunlight, tides, or imported resources), develop systemic memory, stored in biomass, soils, or sediments, that enables them to respond adaptively to disturbances (Odum; Odum, 2006). This is the core of SI: intelligence as thermodynamic optimization through the accumulation, cycling, and reallocation of emergy, as empirically observed in estuarine systems where feedback (e.g., mangrove sediment trapping, otter-mediated trophic cascades) reinforces stability and carbon storage (Carvalho Junior, 2025).

2.2 Thermodynamic self-organization: dissipation, ordering, and persistence

Self-organization in ecological systems is not mere chance. It is driven by energy gradients and regulated by thermodynamic principles. Drawing on Prigogine and Nicolis Prigogine e Nicolis (1985), Jørgensen Jørgensen (2010) and Nielsen et al. Nielsen et al. (2020), researchers have proposed that ecosystems evolve to maximize not only energy dissipation (exergy), but also information (negentropy), i.e., structures that prolong their own existence.

Jørgensen introduced the concept of ecological exergy (Jørgensen, 2007) as a measure of the functional distance between a system and its reference environment and demonstrated that mature systems tend to maximize exergy per unit of invested emergy. This implies a natural selection of more efficient systemic designs. Mangroves, for example, do not merely dissipate solar energy, but organize this dissipation into networks of

roots, nutrient cycling, and refuges, thereby enhancing their persistence.

This perspective aligns with the notion of "intelligence as maximization of persistence" (Ulanowicz, 2014). Systems with high SI are not necessarily the most productive, but those that maintain functionality longer with minimal entropic degradation.

2.3 Emergy analysis and sustainability indicators

The operationalization of Systemic Intelligence (SI) is based on tools from emergy analysis, which were refined by Brown & Ulgiati Brown e Ulgiati (1997), Brown e Ulgiati (2004). They systematized indicators that capture self-regulatory capacity, resource use efficiency, and dependence on external inputs, all of which are important components of SI. The Emergy Sustainability Index ($ESI = EYR/\mathrm{ELR}$) is a metric that combines productivity and environmental impact. A high ESI indicates that the system has adapted to thrive within its biophysical limits. The Environmental Load Ratio (*ELR*) is calculated by dividing non-renewable energy by renewable energy. The Emergy Yield Ratio (*EYR*) is expressed as the total energy generated divided by the energy imported. A value of greater than 1 indicates that the system generates more energetic value than it imports.

Additionally, Bastianoni Bastianoni et al. (2009), Bastianoni, Coscieme e Pulselli (2016) proposed the Emergy Efficiency Index (EEI), which normalizes useful emergy output per unit of high-quality emergy inputs, like electricity or fossil fuels. This indicator is a close approximation of the concept of energetic rationality, which is a crucial aspect of Systemic Intelligence.

2.4 Energetic complexity theory: hierarchy, modularity, and systemic learning

Finally, SI engages with recent advances in complexity theory that incorporate energy as a central variable. Ulanowicz Ulanowicz (2009), in *A Third Window*, argues that biological systems operate in a regime between order and chaos, where the capacity to process information is linked to the amount of emergy available to maintain intermediate structures (e.g., communities, landscapes). This perspective builds on foundational work in resilience theory (Holling, 1973), which established that ecosystems persist not through static equilibrium but by navigating adaptive cycles across multiple stability domains, anticipating the view of intelligence as the capacity to reconfigure while maintaining function.

Self-organization in ecological systems is not mere chance. It is driven by energy gradients and regulated by thermodynamic principles. Building on resilience theory (Holling, 1973), Kauffman Kauffman (1993) demonstrated that complex adaptive systems, whether genetic, ecological, or cognitive, tend to evolve toward 'edge-of-chaos' regimes where robustness and adaptability are balanced through network structure and redundancy. This anticipates the view that systemic intelligence arises not from top-down control, but from the collective dynamics of energy-mediated interactions.

More recently, authors such as Sciubba Sciubba (2020) and Sahraoui et al. Sahraoui, Clauzel e Foltête (2025) have integrated emergy and network theory to demonstrate that ecological networks with high-functional modularity and low hub centrality tend to be more resilient because they distribute "response capacity" across multiple nodes (e.g., redundant keystone species), rather than relying on a single controller. This is analogous to distributed learning in neural networks: intelligence does not reside at a single point but in the topology of energetic interactions.

3 Conceptual Definition of Systemic Intelligence (SI)

Systemic Intelligence (SI) is the emergent ability of ecosystems and socio-ecological systems to perceive, integrate, and adaptively respond to change through the efficient allocation of transformed energy, self-regulation via internal feedbacks, and hierarchical optimization of energy flows. This quality is quantifiable by

systemic indicators, including relative transformity, feedback-to-input ratio, embodied energy density, and efficiency in the use of high-quality resources. This definition critically distinguishes SI from notions of *ecological intelligence* centered on biodiversity or phenotypic plasticity.

SI does not depend on cognition, not even on living organisms, and can be applied to self-organizing abiotic systems (e.g., watersheds, estuaries, geothermal systems), provided they exhibit hierarchical emergy flows with self-regulatory properties. Thus, a mangrove is not "intelligent" because it hosts many species, but because its structure (e.g., aerial roots, redox zones, closed-loop nutrient cycling) results from a long history of selection for energetically efficient pathways that is, from systemic learning mediated by emergy.

3.1 Operational formulation of SI

The Index of Systemic Intelligence (*IIS*) integrates four functional dimensions—hierarchy, autonomy, structure, and prudence—each assigned context-sensitive weights based on theoretical grounding and empirical validation from long-term monitoring in the Peri watershed (Santa Catarina, Brazil). This watershed includes a non-tidal freshwater lake (Lagoa do Peri), connected to the Atlantic Ocean via the ~4 km Sangradouro Channel, which hosts a narrow fringing mangrove at its seaward outlet. The entire system functions as an integrated socio-ecological unit, where land-use changes upstream directly affect hydrological integrity, feedback strength, and keystone species viability downstream.

We propose *IIS* as a composite, dimensionless metric ($0 \leq IIS \leq 1$), derived from four normalized emergy-based indicators:

- ***Tr**** (relative transformity) – reflects hierarchical optimization;
- **(*F/B*)*** (normalized feedback-to-input ratio) – captures systemic autonomy;
- ***EYD**** (relative emergy density) – represents informational storage and structural resilience;
- ***EEI**** (normalized emergy efficiency index) – expresses prudence in the use of nonrenewable resources.

The asterisk (*) denotes normalization to a [0,1] scale, enabling integration across heterogeneous systems (e.g., forests, farms, cities). Normalization is performed relative to empirical minima and maxima observed in analogous systems (see Section 5 and Table 1). For initial applications, we adopt a weighted additive form as defined in Equation (1):

$$\mathrm{IIS} = w_1 Tr^* + w_2 (F/B)^* + w_3 EYD^* + w_4 EEI^*, \tag{1}$$

with $\sum_{i=1}^{4} w_i = 1$

Weight values are calibrated to system type (e.g., natural vs. urban) and validated against long-term field data (see Table 2).

Table 1 - Core variables used in the Index of Systemic Intelligence (*IIS*): definitions, normalization procedures (yielding dimensionless values in [0,1]), and functional interpretations. The min/max/ref quantities are defined by comparison with analogous systems (e.g., Tr_{min} = of a local climax ecosystem; Tr_{max} = of a highly disturbed system)

Variable	Definition	Normalization (0–1)	Interpretation
Relative Transformity (*Tr**)	*Tr* = (Total emergy input in seJ)/(Available energy output in J)	Lower *Tr* → higher efficiency	Indicates more efficient energetic upgrading (e.g., climax forest vs. monoculture)
Normalized feedback-to-input (*F/B**)	*F/B* = (Internally recycled emergy)/(Boundary emergy input)	Values → 1 as internal cycling dominate	System autonomy through self-regulation

Variable	Definition	Normalization (0–1)	Interpretation
Relative emergy density (*EYD)**	*EYD* = (Total emergy stored in seJ)/(Area in m^2 or biomass in g)	Higher *EYD* → greater information storages	Reflects systemic memory and structural resilience
Emergy Efficiency Index (*EEI)**	*EEI* = (Useful emergy output)/(High-quality emergy input, e.g., fossil fuels)	*EEI* → 1 indicates minimal waste	Expresses "energetic prudence"

Source: Authors.

Example of weights for natural systems, specifically applied to estuarine socio-ecological systems: w_1 = 0.3 (hierarchy); w_2 = 0.4 (autonomy—the most critical dimension); w_3 = 0.2 (structure); w_4 = 0.1 (prudence with nonrenewable resources).

$IIS \in [0, 1]$, where $IIS \approx 0$: dependent, unstable system with low structural organization (e.g., irrigated monoculture using fossil-based fertilizers); $IIS > 0.7$: autonomous system with high internal cycling and low entropic degradation (e.g., dense ombrophilous forest, mature coral reef) (Table 2).

Table 2 - Rationale for weighting the four dimensions of the Systemic Intelligence Index (*IIS*), integrating theoretical foundations with empirical evidence from long-term estuarine monitoring

Dimension	Weight	Theoretical Basis	Empirical & Contextual Justification
1. Hierarchy (*Functional organization & nested control*)	w_1 = 0.30	• *Living Systems Theory* by Miller Miller (1978): hierarchical control (e.g., gene → organism → population → ecosystem) is essential for stability. • Gunderson et al. *Panarchy* Gunderson, Holling e Gunderson (2012): cross-scale linkages (e.g., watershed → lagoon → microhabitat) buffer shocks. • Ostrom's *Institutional Analysis and Development (IAD)* framework: nested rule systems (operational collective-choice constitutional) enable adaptive governance (Indiana University, 2026).	In estuaries, hierarchical integrity ensures resilience: e.g., intact riparian corridors (landscape scale) regulate sediment/nutrient flux, supporting macroinvertebrate communities (local scale), which in turn sustain otter prey bases. Degradation at one level (e.g., deforestation upstream) cascades rapidly. Projeto Lontra data (1986–2025) show 68% decline in pup survival in years with upstream land-use intensification—highlighting dependence on functional hierarchy.
2. Autonomy (*Self-regulation, adaptive capacity, agency*)	w_2 = 0.40 *(highest weight)*	• *Resilience Cycle* Resilience Alliance (2026): autonomy enables reorganization after disturbance. • Biggs et al. Biggs et al. (2012) on *ecological thresholds*: systems with high autonomy resist regime shifts. • Berkes Berkes (2007): *adaptive co-management* requires local agency to adjust rules in response to monitoring.	Neotropical otters (*Lontra longicaudis*) are *keystone sentinels* of freshwater health: their persistence depends on system autonomy (e.g., unpolluted inflows, undammed tributaries, intact riparian buffers). Data derive from long-term monitoring (1986–2025) in the Peri watershed (Santa Catarina, Brazil), which includes freshwater lake ecosystems and a narrow fringing mangrove at the mouth of the Sangradouro Channel—the only tidal connection to the ocean (≈4 km downstream from the lake). While the lake itself is non-tidal and not directly influenced by seawater, the estuarine transition zone at the channel's outlet hosts a small but ecologically significant mangrove stand that serves as a sentinel for coastal connectivity and hydrological integrity.

Dimension	Weight	Theoretical Basis	Empirical & Contextual Justification
3. Structure (*Physical & biological configuration: habitat heterogeneity, connectivity*)	$w_3 = 0.20$	• Forman & Godron's *Landscape Ecology* Forman e Godron (1986): patch–corridor–matrix structure governs species movement. • Crooks Crooks (2006): habitat connectivity is critical for wide-ranging carnivores. • Hilty et al. *Guidelines for Connectivity Conservation* Hilty et al. (2020).	Estuarine otters require structural complexity: shelter sites (root tangles, rock crevices), foraging zones (shallow margins, macrophyte beds), and terrestrial corridors for dispersal. LIDAR and telemetry data from Projeto Lontra (2015–2024) show otter home ranges expand by 42% when structural connectivity exceeds 75% (vs. <50% in fragmented zones). While vital, structure is partially compensable (e.g., artificial shelters), hence lower weight than autonomy.
4. Prudence with Nonrenewable Resources (*Sustainable use of abiotic capital: water, soil, fossil energy*)	$w_4 = 0.10$	• Daly's *Steady-State Economy* Daly (1991): nonrenewables must be used at rates $\leq$ substitution by renewables. • Rockström et al.'s *Planetary Boundaries* Rockström et al. (2009): freshwater use & biosphere integrity are core boundaries. • Millennium Ecosystem Assessment Millennium Ecosystem Assessment (2005): depletion of non-renewable natural capital (e.g., groundwater, phosphorus) undermines long-term provisioning.	In the Peri watershed, the primary nonrenewable constraint is groundwater over-extraction for tourism infrastructure, lowering lake levels—critical for fish diversity. However, unlike autonomy or structure, this pressure is currently moderate and manageable through zoning and reuse policies. Thus, while essential for intergenerational equity, it exerts less immediate pressure on otter viability—justifying the lowest weight.

Source: Authors.

3.2 Manifestations of Systemic Intelligence (SI) across organizational levels

Systemic Intelligence (SI) is not confined to a single scale but emerges across hierarchical levels, from abiotic processes to socio-ecological systems, each expressing distinct yet interconnected patterns of energetic organization. The manifestations of SI reflect how feedback, hierarchy, redundancy, and efficiency are enacted contextually, depending on the system's structural and functional constraints. Table 3 synthesizes these scale-dependent expressions, linking observable systemic behaviors to their underlying emergy-based signatures. This multi-level perspective underscores a key principle: SI is a relational property of networked energy-matter flows, rather than an attribute of any single component.

Table 3 - Manifestations of Systemic Intelligence (SI) across organizational levels, with corresponding emergy-based indicators. SI expresses itself contextually, from abiotic self-regulation to socio-ecological integration, through scale-specific patterns of energetic efficiency, feedback dominance, functional redundancy, and hierarchical optimization

Level	Manifestation of SI	Associated Emergy Indicator(s)
Abiotic process	Self-regulation of flows (e.g., thermocline in a lake, redox zones in a mangrove)	*EYD*, *F/B*
Individual organism	Efficient energy allocation (e.g., phenology synchronized with solar/tidal emergy pulses). This capacity for dynamic energy allocation reflects the modular optimization strategies long recognized in plant biology (Harper, 1981), wherein organisms adjust resource partitioning in response to environmental feedback, not through cognition, but via evolved physiological rules that maximize persistence.	Tr^* (local), *EEI*
Population/community	Functional redundancy with low transformity overlap (e.g., species occupying complementary energetic niches)	*EEI*, *EYD*

Level	Manifestation of SI	Associated Emergy Indicator(s)
Ecosystem	Balance between accumulation (biomass) and dissipation (respiration) via internal feedback	*F/B*, *Tr**
Socio-ecological system	Integration of renewable inputs with low dependence on nonrenewable emergy (e.g., agroforestry with green manure)	*EEI*, %Renewable, ESI (Emergy Sustainability Index)

Source: Authors.

Efficient energy allocation in individual organisms, such as phenological tuning to solar/tidal emergy pulses, reflects evolved economic strategies shaped by natural selection (Ricklefs; Relyea, 2014), wherein organisms adjust resource partitioning to maximize persistence within energetic constraints. This capacity constitutes a foundational layer of Systemic Intelligence: intelligence not as cognition, but as embodied thermodynamic responsiveness.

3.3 Critical distinction: SI ≠ isolated efficiency

It is essential to emphasize that high productivity or high energetic efficiency *per se* do not imply high Systemic Intelligence (SI). SI transcends momentary performance metrics by evaluating how a system sustains functionality over time through thermodynamically intelligent design. For instance, a highly productive system, such as a transgenic soybean monoculture, may exhibit low SI. Its feedback-to-input ratio (*F/B*) is typically very low (minimal internal cycling), and its relative transformity (Tr^*) is poor due to heavy reliance on high-transformity external inputs (e.g., synthetic fertilizers, pesticides, and fossil-fuel-based machinery).

Conversely, a late-successional ecosystem, such as a mature Atlantic Forest patch, may display low net productivity yet high SI, as it prioritizes persistence over output. In this case, energy is channeled into storage (biomass, soil organic matter), redundancy, and closed loop feedbacks, thereby maximizing longevity per unit of emergy invested. This distinction is central to the concept: SI measures systemic wisdom, not instantaneous yield. It shifts the focus from *how much* a system produces to how wisely it endures.

4 Analogy with Neural Networks. Emergy Networks as an Architecture for Systemic Intelligence

The comparison between artificial neural networks (ANNs) and ecosystems is often made metaphorically, suggesting that "nature learns like a neural network." However, this analogy only acquires theoretical rigor when reformulated in energetic terms, grounded in H.T. Odum's emergy theory. We therefore propose reinterpreting ANNs not as *cognitive* models, but as *functional* models of hierarchical flow processing, where "information" is encoded in differences of energy quality, not in bits.

Table 4 presents an operational (not merely formal) correspondence between the components of an ANN and those of an Emergy Network (E^N). An ecological system modeled as a network of emergy flows exhibiting hierarchy, feedback, and self-regulation.

Table 4 - Functional correspondence between Artificial Neural Networks (ANNs) and Emergy Networks (E^N)

Component	Artificial Neural Network (ANN)	Emergy Network (E^N)	Theoretical basis
Basic unit	Neuron (weighted sum + activation)	High-transformity node (e.g., apex predator, ecosystem engineer, organic soil) a point where multiple low-quality flows are integrated into high-quality structure	Odum Odum (1996): transformity as "organizational power"; Bastianoni et al. Bastianoni et al. (2007)

Component	Artificial Neural Network (ANN)	Emergy Network (E^N)	Theoretical basis
Connection	Synapse with weight w_{ij} (adjustable via backpropagation)	Adjustable emergy flow E_mY_{ij} (e.g., transferred biomass, chemical signal, transported sediment), modulated by feedback (e.g., competition, mutualism, nutrient cycling)	Brown & Ulgiati Brown e Ulgiati (1997): flows as dynamic variables in emergy analysis
Activation function	*f(z)* = 1/(1 + e^{-z}) (e.g., sigmoid)	Emergy threshold for state change (e.g., soil nutrient saturation point; coral thermal tolerance limit; tipping point in regime shift)	Jørgensen Jørgensen (2007): exergy as a measure of functional distance from reference state
Input	Data vector *x*	External emergy flows (e.g., solar radiation, tides, allochthonous inputs)—E_mY_{solar}, $E_mY_{ti}d_{al}$	Odum Odum (1988): renewable inputs as the basis of systemic autonomy
Output	Prediction $\hat{y}$	System functional output (e.g., net productivity, stored biomass, resilience measured by recovery time Δt after disturbance)	Ulanowicz Ulanowicz (2014): persistence as the system's objective function
Learning	Loss minimization via w_{ij} adjustment	Selection of energetically efficient pathways via natural feedback, increasing *F/B*, reducing relative transformity, increasing useful emergy density	Odum & Odum Odum e Odum (2006): "ecosystems learn over time through the accumulation of energetic memory"
Optimization goal	Minimize mean squared error	Maximize the Index of Systemic Intelligence (SI)—i.e., maximize persistence per unit of emergy invested	This paper (Section 3)
Regularization mechanism	Dropout, L1/L2 regularization	Functional redundancy with low transformity overlap (e.g., multiple species occupying complementary energetic niches)	Bastianoni et al. Bastianoni et al. (2009): emergy efficiency as an indicator of robustness

Source: Authors.

In a mangrove, the aerial roots of *Rhizophora mangle* act as high-transformity nodes, integrating solar, tidal, and chemical emergy into structures resistant to anoxia. The "synaptic flow" between phytoplankton and fiddler crab larvae is modulated by chemical feedback (e.g., root exudates stimulating sulfate-reducing bacteria). Following a disturbance (e.g., increased salinity), the system "relearns" by reconfiguring flows, not through computation, but via thermodynamic selection. Pathways with lower entropic dissipation and higher *F/B* ratios persist.

This functional analogy avoids anthropomorphism while preserving explanatory power: both systems, ANNs and E^N, optimize adaptive behavior through the dynamic reweighting of connections, albeit via different physical substrates (electrical signals vs. emergy flows).

4.1 Limits and advantages of analogy

The analogy does not imply cognition in nature; rather, it recognizes that both systems, ANNs and Emergy Networks (E^N), function as information processors via hierarchical flows, albeit through fundamentally different mechanisms. In ANNs, information is representational (data $\rightarrow$ prediction). In E^N, information is embodied (emergy $\rightarrow$ persistent structure). The key advantage is operational. It enables the transfer of network analysis methods, such as centrality, modularity, and critical path analysis, from computational science to the domain of emergy-based systems.

This makes it possible, for instance, to identify high-transformity nodes whose loss would collapse Systemic Intelligence (SI), analogous to hub removal in neural networks; simulate "lesions" in the system (e.g., removal of an ecosystem engineer) and quantify the resulting impact on SI; and train hybrid models (e.g., ANNs fed with

emergy-based data) to predict regime shifts and tipping points. This approach paves the way for a physics-based science of systemic intelligence, grounded in thermodynamics and energy hierarchy, rather than one reliant on metaphor or anthropomorphism.

5 Applications: Monitoring Systemic Intelligence Through Quantifiable Indicators

The concept of Systemic Intelligence (SI) only becomes useful for applied science when translated into measurable, replicable, and scalable protocols. Building on the operational definition (Section 3) and the foundations of emergy analysis (Section 2), we present strategies to calculate, compare, and monitor SI across three system types: natural ecosystems, agroecosystems, and urban systems. The focus lies on established indicators, not on proposing new theories, but on creating novel, functionally meaningful combinations of already-validated metrics.

5.1 General protocol for calculating the Index of Systemic Intelligence (IIS)

The operationalization of Systemic Intelligence hinges on a transparent, stepwise methodology that bridges theoretical foundations and field application. Table 5 outlines a standardized workflow. It starts with clear system delimitation, proceeding through rigorous emergy accounting, followed by context-sensitive normalization and weighting, and culminating in the computation and interpretation of the *IIS*.

It's important to note that the protocol focuses on diagnostic depth, which means that it doesn't just give a single index value. It also gives component-level insights (like low autonomy or poor energetic prudence) that help guide targeted interventions. By integrating established tools (e.g., GIS, AHP) and validated indicators, this approach supports longitudinal monitoring, cross-system comparison, and evidence-based decision-making in conservation, regenerative design, and adaptive governance.

Table 5 - Four-step protocol for calculating the Index of Systemic Intelligence (*IIS*), designed to ensure reproducibility, scalability, and contextual relevance across diverse system types from natural ecosystems to urban landscapes.

Step	Action	Recommended tools
1. System delimitation	Define spatial, temporal, and functional boundaries (e.g., watershed, production unit, urban neighborhood). Include renewable (solar, tidal, wind) and nonrenewable (fossil, imported) emergy flows.	Land-use maps, remote sensing, flux inventories: e.g., EmSim, Scale, Network Analysis (Ulanowicz; Heymans; Egnotovich, 2000), hydrological/nutrient budgets).
2. Emergy analysis	Quantify all input, storage, output, and feedback flows in solar emjoules (seJ). Compute transformity, emergy density, *F/B*, *EEI*, *%Renewable*, *EYR*, *ELR*, and *SI*.	Software: Spartacus (Bastianoni), standardized spreadsheets (e.g., Emergy Synthesis Handbook protocol).
3. Normalization and weighting	Normalize indicators to [0,1] (see Section 3). Assign context-specific weights (e.g., emphasize *F/B* for natural systems; prioritize *EEI* for urban systems).	Multicriteria decision tools (e.g., AHP), calibration against reference case studies.
4. *IIS* calculation	Apply the equation: $IIS = w_1 \cdot Tr^* + w_2 \cdot (F/B^* + w_3 \cdot EYD^* + w_4 \cdot EEI^*$	
4. *IIS* calculation	Generate a report including absolute *IIS* value, temporal trend (Δ*IIS*/year), and component-level diagnosis (e.g., "low autonomy: ($F/B^* = 0.2$").	Visualization: dashboards, thematic maps (e.g., spatialized SI via GIS).

Source: Authors.

5.2 Case 1: Freshwater Lake with Estuarine Transition Zone (System with High Expected SI)

Objective: Assess Systemic Intelligence in a freshwater-dominated socio-ecological system connected to the ocean via a tidal channel, where a narrow fringing mangrove at the estuarine outlet serves as a sentinel of hydrological connectivity and coastal integrity.

Data derive from long-term monitoring (1986–2025) conducted by *Projeto Lontra* in the Peri watershed (Santa Catarina, Brazil) (Carvalho Junior, 2025). While Lagoa do Peri itself is a non-tidal freshwater lake, it is linked to the Atlantic Ocean through the ~4 km Sangradouro Channel, which hosts a small but ecologically significant fringing mangrove at its seaward mouth. This estuarine transition zone functions as a critical indicator of system-wide autonomy. Its health reflects upstream land-use practices, hydrological regulation, and feedback integrity across the entire watershed (Table 6).

Table 6 - Key emergy-based indicators for assessing Systemic Intelligence (SI) in the Peri watershed's estuarine transition zone (fringing mangrove at the Sangradouro Channel outlet).

Note: Weights were adjusted to emphasize autonomy (w_2 = 0.5), as hydrological connectivity and feedback integrity in the estuarine transition zone are highly sensitive to upstream anthropogenic pressures, a pattern consistently observed in 39 years of Projeto Lontra monitoring (Carvalho Junior, 2025).

Indicator	Data Collection Method	Expected Value in Mature Mangrove
Transformity (*Tr*)	Biomass sampling (leaves, roots, sediment); emergy calculation using transformity tables for mangroves (e.g., Brown and Bardi (Brown; Bardi, 2001); Liu et al. Liu et al. (2021); Qin et al. Qin, Wong e Tam (2000)).	Low *Tr* for sedimented organic matter (high efficiency in solar/tidal energy incorporation).
F/B	Estimate: *Feedback*: decomposition, crab excretion, root exudates; *External input*: solar radiation, tides, rainfall.	*F/B* > 2 (internal cycling dominant).
EYD	Total emergy/area (seJ/m^2·yr) — via inventory of live + dead biomass + organic sediment.	> 10^{12} seJ/m^2·yr (typical for mature intertidal zones).
EEI	Useful emergy (e.g., sustainable fishing, carbon sequestration)/nonrenewable input emergy (e.g., monitoring equipment).	*EEI* $\approx$ 1 (virtually zero fossil inputs).

Source: Authors.

***IIS* Interpretation**:

• ***IIS* > 0.75**: High self-regulation—observed only in specific monitoring years (e.g., 1998, 2005, 2019) characterized by minimal upstream land-use intensification, intact riparian corridors, and low anthropogenic pressure on the Sangradouro Channel. These peaks reflect the system's inherent capacity for autonomy when external stressors are temporarily reduced, and they indicate priority zones for *in situ* conservation.

• ***IIS* < 0.4**: Critical feedback loss—consistently recorded during periods of upstream deforestation, groundwater over-extraction, or intensified urban discharge into the lower Sangradouro Channel (e.g., 2010–2015). This signals an urgent need for hydrological reconnection, riparian restoration, and sanitation infrastructure upgrades.

Crucially, the *IIS* value is not a static property of the entire watershed, but a dynamic indicator that captures the state of the estuarine transition zone—specifically, the narrow fringing mangrove at the seaward outlet of the Sangradouro Channel. While upstream segments of the channel suffer from sewage inputs and reduced connectivity, the mangrove sentinel responds to integrated watershed conditions. Thus, an *IIS* > 0.75 does not deny local degradation; rather, it reveals windows of systemic resilience that emerge when cumulative pressures fall below critical thresholds—precisely the states we must strive to restore and maintain through adaptive governance.

Practical application: Integrate *IIS* into adaptive management of the Natural Monument (MONA) Protected Area - Lagoa do Peri, complementing structural metrics like the Habitat Integrity Index (HII). By monitoring changes in energetic autonomy and feedback strength, the *IIS* provides early warning of systemic degradation, frequently before biodiversity loss is noticeable.

5.3 Case 2: Agroecosystem (Socio-Ecological System with Potential for High SI)

Objective: Compare agricultural systems based on systemic intelligence, not just productivity, using empirical emergy data from the RH3 region (Santa Catarina, Brazil).

Rather than relying on hypothetical values, we ground our *IIS* comparison in the empirical emergy analysis of the RH3 agribusiness region (Carvalho Junior; Birolo, 2022), which encompasses 38 municipalities and is a major national exporter of pork and poultry. The study quantified all renewable and nonrenewable emergy flows supporting soy, swine, and chicken production, yielding key indicators directly translatable into the *IIS* framework.

Table 7 contrasts the Systemic Intelligence (*IIS*) profiles of the actual RH3 agro-system with a hypothetical community-based agroforestry system, demonstrating how *IIS* reveals fundamental differences in energetic organization that conventional metrics (e.g., yield, GDP) obscure. The RH3 data show an extremely low contribution from local renewable sources (R% $\approx$ 1.4%) and a high dependence on external, high-transformity inputs (infrastructure/services = 33,67 E+18 seJ/yr), resulting in a very low feedback-to-input ratio (F/B $\approx$ 0.1). This translates into a low *IIS* (0.1–0.3), reflecting vulnerability to external shocks and minimal internal cycling.

Table 7 - Empirical basis for Systemic Intelligence (*IIS*) assessment in southern Brazilian agroecosystems, derived from emergy analysis of the RH3 region (Carvalho Junior; Birolo, 2022).

System	Expected *IIS*	Empirical Emergy Diagnosis
RH3 Agribusiness (soy-poultry-swine)	Low (*IIS* $\approx$ 0.1–0.3)	• High *Tr*: Extreme dependence on fossil-based inputs (fertilizers, machinery, infrastructure) • *F/B* $\approx$ 0.1: Minimal internal cycling; 98.6% of emergy is non-local • *EEI* < 0.2: High waste of high-quality emergy (ELR = 11.75) • *ESI* = 0.10: Very low sustainability (Carvalho Junior; Birolo, 2022)
Community-based agroforestry	High (*IIS* $\approx$ 0.6–0.8)	• Moderate *Tr*: Renewable inputs (green manure, compost, legumes) • *F/B* > 1: Internal cycling via litter, biological N-fixation, closed-loop nutrients • *EEI* > 0.7: Low external dependency; high emergy efficiency (Cavalett; Queiroz; Ortega, 2006)

Source: Authors.

In contrast, community-based agroforestry systems—such as those modeled by Cavalett et al. (2006) for southern Brazil—leverage local renewable inputs (green manure, biological N-fixation) and foster strong internal feedback loops (litter decomposition, nutrient recycling), achieving *F/B* > 1 and *EEI* > 0.7. This yields a high *IIS* (0.6–0.8), embodying energetic prudence and adaptive capacity.

This empirical grounding transforms *IIS* from a conceptual tool into a diagnostic metric for real-world policy. It indicates that the RH3's economic success masks a profound systemic fragility: its ELR of 11.75 and ESI of 0.10 confirm high environmental loading and low sustainability (Carvalho Junior; Birolo, 2022). The *IIS* framework makes this visible by quantifying the wisdom of flow, not just the volume of output.

Practical application: Certification of Energetically Intelligent Food Systems (EIFS), complementing labels such as *Organic* or *Fair Trade*. EIFS would require: (i) F/B > 1 (net internal cycling), (ii) EEI > 0.7 (efficient use of nonrenewables), and (iii) positive Δ*IIS* over a 3–5 year monitoring period. Such a label would empower consumers and policymakers to support systems actively regenerating their energetic foundations, aligning market incentives with long-term biophysical sustainability.

A key advantage of the Index of Systemic Intelligence (*IIS*) lies in its capacity to track systemic change

over time, making it particularly valuable for evaluating socio-ecological interventions. The difference $\Delta IIS = IIS_{\text{post-intervention}} - IIS_{\text{Baseline}}$ serves as a robust, physics-based indicator of program effectiveness, not merely measuring outputs (e.g., hectares restored, families trained), but capturing whether the underlying energetic architecture of the system has genuinely improved.

For instance, in long-term initiatives such as Projeto Lontra (Instituto Ekko Brasil) which integrates neotropical otter conservation, community-based income generation (e.g., artisanal fishing, ecotourism), and environmental education across estuarine landscapes in southern Brazil, ΔIIS can reveal whether interventions have strengthened feedback loops (e.g., through participatory monitoring increasing local stewardship), reduced dependence on external subsidies (e.g., replacing diesel-powered boats with solar-assisted alternatives), or enhanced functional redundancy (e.g., diversifying livelihoods). A threshold of $\Delta IIS > 0.2$ over 5 years is proposed as a benchmark for systemic success, indicating a meaningful shift toward greater autonomy, efficiency, and resilience, beyond short-term gains.

Effective implementation of SI-based policies requires adaptive governance frameworks that foster learning, polycentric decision-making, and inclusion of local knowledge (Folke et al., 2005). This aligns with initiatives such as Projeto Lontra, where community monitoring not only improves data quality but also strengthens feedback loops between ecological and social subsystems.

Building on this, *IIS* offers a foundation for innovative governance tools, such as the certification of Energetically Intelligent Food Systems (EIFS). While existing labels like Organic (focused on input restriction) or Fair Trade (focused on social equity) address important dimensions, they rarely assess how wisely a system organizes energy flows over time. EIFS would fill this gap by requiring, for instance: (i) $F/B > 1$ (demonstrating net internal cycling), (ii) $EEI > 0.7$ (efficient use of nonrenewable resources), and (iii) positive ΔIIS over a 3–5 year monitoring period. Such a label would empower consumers and policymakers to support not just less harmful production, but systems actively regenerating their energetic foundations, aligning market incentives with long-term biophysical sustainability.

5.4 Case 3: City (Anthropogenic System with Challenge of Raising SI)

Objective: Identify opportunities for regenerative urban transition.

Urban systems, often characterized by high throughput of nonrenewable emergy and weak internal feedback, represent a critical frontier for applying Systemic Intelligence. Table 8 translates the *IIS* framework into actionable, subsystem-specific metrics and targets, moving beyond generic sustainability goals to energetically grounded urban planning.

Table 8 - Application of Systemic Intelligence (SI) indicators to key urban subsystems, with proposed targets for regenerative transition, shifting cities from energy-dependent to energy-autonomous systems.

Urban Component	Relevant Emergy Indicator	SI Target
Green infrastructure	*EYD* of green areas / total area; *F/B* in parks (e.g., local decomposition vs. waste removal).	Increase EYD^* by 30% in 10 years.
Waste management	*EEI* = recovered emergy (compost, biogas)/emergy of collection & disposal.	$EEI^* > 0.5$ (currently ≈ 0.1 in most cities).
Mobility	*Tr* of public transport system (lower = more efficient); comparison with private motorized transport.	Reduce average *Tr* by 40%.
Governance	% of decisions based on emergy data (e.g., municipal energy budgeting).	Incorporate *IIS* into *Systemic Master Plan*.

Source: Authors.

For green infrastructure, increasing emergy density (EYD^*) reflects not just more green space but functionally integrated vegetation that stores solar information and enhances local cycling (e.g., parks that compost

on-site rather than exporting waste). In waste management, raising EEI^* from ~0.1 to >0.5 signifies a shift from linear disposal to circular metabolisms, where organic waste becomes a source of emergy (biogas, compost) rather than a sink.

For mobility, reducing the transformity (Tr) of transit systems targets the quality of energy used (e.g., shifting from private cars powered by refined fossil fuels to electric buses fed by renewables), not just emissions or ridership. Finally, embedding emergy accounting into governance ensures decisions are informed by systemic energetics, paving the way for a Systemic Master Plan where budgeting, zoning, and infrastructure investment align with long-term persistence, not short-term expediency.

Together, these targets operationalize urban resilience as thermodynamic intelligence in action. To address the distinct energetic dynamics of urban systems, characterized by high reliance on imported, high-quality emergy and often weak internal feedback, we propose a tailored variant: the Urban Systemic Intelligence Index (IIS_u). This adaptation maintains the core structure of the *IIS* but rebalances the weights to reflect urban priorities (Equation 2):

$$IIS_{\mathrm{u}} = 0.25 \cdot Tr^* + 0.25 \cdot (F/B^*) + 0.25 \cdot EEI^* + 0.25 \cdot \%R^* \quad (2)$$

Equal weighting emphasizes four pillars of urban metabolic health: hierarchical efficiency (Tr^*), functional autonomy (F/B^*), resource prudence (EEI^*), and, critically, renewable energy reliance ($\%R^*$), the proportion of total emergy from solar, wind, tidal, and biomass sources). This explicit inclusion of $\%R^*$ underscores the urgency of decoupling cities from nonrenewable subsidies, aligning with global decarbonization goals while grounding them in biophysical reality.

Unlike productivity or GDP-centric metrics, IIS_u prioritizes persistent functionality. A city that powers its transit with solar, recycles nutrients locally, and makes budgetary decisions based on emergy flows scores higher, not because it is larger or wealthier, but because it is wiser in its energy use.

A transformative application of IIS_u lies in its integration into a Systemic Human Development Index (*SHDI*), an evolution beyond the traditional Human Development Index (*HDI*). While *HDI* combines health, education, and income, it remains blind to the energetic foundations of those achievements. A high-*HDI* city may depend on volatile fossil imports or degrade its hinterlands to sustain consumption.

The *SHDI* would augment *HDI* dimensions with IIS_u (e.g., $SHDI = 0.6 \cdot HDI + 0.4 \cdot IIS_u$), ensuring that human well-being is assessed *in tandem* with systemic viability. Municipalities could then track not only life expectancy or literacy but also whether their development pathway is thermodynamically sustainable, rewarding innovations like district composting, renewable microgrids, or emergy-informed land-use planning. In doing so, SHDI shifts the development paradigm from growth at all costs to flourishing within energetic means, offering a robust compass for 21st-century urban governance.

Practical application: Integration of IIS_u into a *Systemic Human Development Index (SHDI)*—an advancement beyond the traditional *HDI*.

5.5 Operational Limitations and Challenges

The implementation of the Index of Systemic Intelligence (*IIS*) inevitably encounters practical constraints, yet each can be effectively mitigated through methodological adaptation and institutional collaboration. A primary concern is the cost and time investment required for full emergy analysis, traditionally perceived as demanding extensive data and specialized expertise. However, this barrier has been substantially reduced by the development of simplified, tiered approaches, most notably the Rapid Emergy Assessment (REA) protocol (Bastianoni; Coscieme; Pulselli, 2016). REA prioritizes critical flows (e.g., solar input, key imports, major feedbacks) and leverages proxy data (remote sensing, agricultural statistics, land-use maps) to estimate core indicators (Tr, F/B, EYD, EEI) with sufficient accuracy for monitoring, comparison, and decision support, making *IIS* viable even in community-based or low-budget contexts, such as participatory conservation initiatives

in coastal Brazil.

Equally important is the question of scalability. The *IIS* framework is inherently scalable. It can be applied consistently across vastly different spatial and functional units, from a single agroforestry plot or mangrove channel (micro-watershed scale) to a family farm, a protected area, or an entire river basin, without loss of conceptual integrity. Granularity is adjustable. High-resolution assessments (e.g., plot-level biomass inventories) suit impact evaluation of localized interventions, while coarser, GIS-integrated estimates support regional planning. This adaptability ensures that *IIS* remains relevant across governance levels, from grassroots monitoring (e.g., Projeto Lontra volunteers tracking local feedback) to policy design at state or bioregional scales.

Finally, successful adoption hinges on capacity building. While emergy analysis was once confined to a small academic circle, training is now increasingly accessible and practical. Structured courses, workshops, and online resources are offered by institutions with deep roots in systems ecology, including in Brazil (UFSC, UNESP), Italy (University of Siena), USA (University of Florida), and China (University of Chinese Academy of Sciences), and open-source software lowers the technical entry barrier.

Experience from long-term monitoring initiatives—such as *Projeto Lontra* in southern Brazil—demonstrates that technicians, educators, and even local stewards can be effectively trained to collect essential field data and interpret trends in the Index of Systemic Intelligence (*IIS*). This capacity-building transforms the *IIS* from an esoteric expert metric into a shared diagnostic language, co-produced across scientific, community, and governance spheres. Rather than being weakened by practical constraints, the *IIS* is refined through real-world application, ensuring it remains both scientifically rigorous (grounded in thermodynamic principles) and socially embedded (responsive to local knowledge and needs). To clarify the conceptual shift introduced by Systemic Intelligence, Table 9 contrasts the traditional approach to sustainability assessment with the SI framework.

Table 9 - Comparative overview of traditional sustainability assessment versus the Systemic Intelligence (SI) approach. The SI framework shifts the focus from static snapshots of structure to dynamic diagnostics of function, integrating ecological, economic, and social dimensions through a common biophysical currency: emergy (embodied energy).

Dimension	Traditional Approach	Systemic Intelligence (SI) Approach
What is assessed?	*What exists*: biodiversity, land cover, biomass	*How it works*: autonomy, efficiency, feedback strength, resilience
Temporal perspective	Static (single-point snapshot)	Dynamic (trends, adaptive cycles, systemic learning)
Scope	Sectoral (e.g., conservation vs. agriculture)	Integrated (nature–economy–society as coupled flows)
Methodological basis	Subjective or ad hoc composite indices	Physics-based (emergy as a universal unit of real wealth)

Systemic Intelligence does not eliminate conventional ecological indicators; rather, it enhances them by incorporating a systemic dimension that is absent: the wisdom of flow. Where traditional tools ask, *"How much?"* SI asks *"How wisely does the system endure?"*, shifting evaluation from output to process, from stock to flow, and from isolation to integration.

6 Final Considerations

Systemic Intelligence (SI) is not a poetic metaphor but a robust epistemological proposal. It repositions intelligence as an emergent property of organized energy flows, rather than an exclusive attribute of brains or algorithms. Ecosystems, shaped over billions of years by thermodynamic evolution, have developed structures that enable self-regulation, adaptive responses to disturbance, and long-term persistence through the efficient allocation of transformed energy. Recognizing this allows us to move beyond merely describing nature toward a science that actively learns from it.

However, anthropomorphism should really be avoided. Claiming that a mangrove "decides" or "plans"

is as inadequate as asserting that a neural network "understands" poetry. What we propose is more precise. Ecological systems operate as if intelligent, not through intentionality, but via natural selection of energetically efficient designs. This intelligence is materialist, measurable, and modelable.

Far from being a purely conceptual exercise, the Index of Systemic Intelligence (*IIS*) has proven effective as a diagnostic and policy-guiding tool through its continuous application in real socio-ecological contexts, from mangroves monitored for four decades to regional agroecosystems. It demonstrates that nature's systemic wisdom can indeed be measured and tracked over time. Moreover, it can be actively harnessed to inform sustainable governance.

The Index of Systemic Intelligence (*IIS*), grounded in transformity, feedback-to-input ratio, emergy density, and emergy efficiency, offers a common language for ecologists, engineers, planners, and policymakers, bridging disciplines through shared thermodynamic principles. This unified framework allows for a more coherent assessment of complex socio-ecological systems by translating ecological dynamics into measurable, comparable indicators that transcend disciplinary boundaries. It thus provides a foundation for collaborative governance that respects both scientific rigor and local knowledge, enabling more integrated approaches to sustainability challenges.

In light of this, we propose the following research and action agenda: (i) expanded operationalization of *IIS*—developing simplified protocols (e.g., Rapid Systemic Intelligence Assessment) for field application by conservation teams such as those in Projeto Lontra, enabling long-term monitoring of socio-ecological landscapes; (ii) future work should integrate SI with long-term monitoring, as piloted in estuarine socio-ecological systems (Carvalho Junior, 2025), and expand participatory modeling to include Indigenous and local ecological knowledge; (iii) hybrid modeling—integrating emergy analysis with complex network theory and machine learning to simulate regime shifts based on *IIS* dynamics; (iv) interepistemic dialogue—articulating SI with traditional knowledge systems (e.g., Indigenous landscape stewardship, ancestral peasant practices), which often intuitively embody principles of energetic autonomy and local feedback, and with ecological justice theories, to ensure that Systemic Intelligence is not weaponized to justify exclusion or technocratic control.

In a world marked by interconnected crises—climatic, biological, and social—the question is no longer whether we must change, but how to change wisely. Systemic Intelligence reminds us that Earth has already invented, tested, and refined, over geological epochs, strategies for thriving within limits. Perhaps the most intelligent course of action today is to let ourselves be taught by the very logic of living systems, not as masters of nature, but as its attentive apprentices.

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