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Case Report

A Thermodynamic Case Report of Ecological Energy Degradation and Anergy Production Ecological

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Abstract

Thermodynamic principles have long been applied to ecological systems, yet a minimal formal structure capable of describing energy degradation and useful work within ecosystems remains limited. In this case report, It is presented a simplified thermodynamic formulation based on the decomposition of energy into useful energy and anergy. A basic ecological system is described using measurable variables such as biomass and metabolic potential, treated as conjugated thermodynamic variables. From these quantities, key thermodynamic state functions-including internal energy, enthalpy, entropy, useful energy, and anergy-can be defined. The formulation illustrates how irreversible processes generate anergy through entropy production and how biological work emerges from interactions between biomass and metabolic potential. This minimal framework demonstrates how ecological systems can be described using classical thermodynamic structure while accounting for the irreversible degradation of energy quality.

Abbreviations: A -Anergy (Degraded Energy Produced by Irreversible Processes); B - Biomass (Total Organized Biological Matter in The Ecosystem); E - Exergy or Useful Energy Stored in Biological Organization; Ein - Incoming Energy Flux to The Ecosystem; Em - Emergy (Cumulative Historical Energy Required to Generate Ecological Structure); G - Ecological Gibbs Free Energy; H -Ecological Enthalpy; k - Proportionality Constant Related to Metabolic Activity and Environmental Conditions; O – Onsager Thermodynamic Potential; S - Total Entropy; S_{rev} -Reversible Entropy Exchange with the Environment; S_{gen} - Entropy Generated Internally by Irreversible Processes; T - System Temperature; T_0 - Environmental Reference Temperature; Tr - Transformity (Ratio Between Emergy And Useful Energy at a Given Hierarchical Level); U - Internal Energy of the Ecological System; δW_{eco} - Ecological Work Associated with Biomass Change; δQ - Heat Exchange with the Environment; μ - Metabolic Potential (Thermodynamic Variable Conjugate to Biomass); Φ(B) - Dissipative Function Representing The Capacity Of The Ecosystem to Transform Incoming Energy into Anergy; α - Scaling Exponent Describing How Dissipative Capacity Depends on Biomass

Introduction

Ecological systems are open thermodynamic systems that transform and degrade energy while sustaining organized biological structures. Since the early work of Howard T. Odum, ecosystems have been understood as networks maintained by continuous energy throughput and dissipation, where biological organization emerges from energy flows and ecological interactions [1-3]. Thermodynamics provides a natural framework to describe these processes, yet most ecological thermodynamic models remain largely qualitative. A key limitation is the lack of a simple formulation that explicitly accounts for the degradation of energy quality during ecological transformations. From a thermodynamic perspective, energy can be decomposed into useful energy and degraded energy. These components are commonly referred to as exergy and anergy, respectively [4]. This decomposition allows the internal energy of the system to be written as U=E+A, E represents useful energy stored in organized structures and A represents anergy produced through irreversible processes. Because entropy production accompanies irreversible transformations, anergy increases as energy is progressively degraded. A complementary relation linking anergy with reversible entropy can be expressed through an Onsager-type potential. Recent discussions in thermodynamics suggest that additional principles may be required to describe complex non-equilibrium systems [5]. In this context, a formulation based on energy quality degradation has been proposed to describe the thermodynamics of ecological organization [6]. This approach provides a minimal framework for representing how ecosystems transform incoming energy into biological structure while simultaneously generating entropy and degraded energy.

Case Presentation

A simplified ecological system is considered consisting of a photosynthetic microbial community interacting with its surrounding environment. The system exchanges energy with the environment mainly through solar radiation and biochemical metabolism. The macroscopic thermodynamic state of the ecosystem can be described using biomass as an extensive state variable B, representing the total amount of living biological matter present in the system. The conjugated intensive variable is defined as the metabolic potential μ, which characterizes the energetic capacity of the biological system to transform environmental resources into metabolic work. The ecological work associated with changes in biomass can therefore be expressed as

$$\delta W_{eco}=-\mu dB \qquad 1)$$

indicating that metabolic potential acts as the generalized force driving changes in ecological organization. The internal energy of the ecological system follows the first law of thermodynamics

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$$dU=TdS_{rev}-\mu dB \qquad 2)$$

where heat exchange with the environment is represented by $\delta Q=TdS_{rev}$ with Srev representing reversible entropy exchange. The total entropy variation of the ecological system includes both reversible and irreversible contributions and can therefore be expressed as

$$dS=+dS_{rev}+dS_{gen} \qquad 3)$$

where dSgen corresponds to entropy generated internally by irreversible metabolic processes. Using these variables, an ecological enthalpy function can be defined as

$$H = U + \mu B \qquad 4)$$

which represents the energetic contribution associated with maintaining biomass within the ecosystem. Under conditions of constant temperature, the ecological Gibbs free energy becomes

$$G=U+\mu B-TS_{rev} \qquad 5)$$

describing the energy available to sustain ecological processes. From the perspective of energy quality, the internal energy of the system can be decomposed into useful energy stored in biological organization and Degraded Energy Produced by Irreversible Processes

$$U = E + A \qquad 6)$$

where E represents organized useful energy and A represents anergy. To describe the thermodynamic contribution of irreversible transformations, the Onsager thermodynamic potential is introduced as

$$O=A+TS_{rev} \qquad 7)$$

which links anergy production with reversible entropy exchange and provides a compact thermodynamic description of energy degradation and organization within ecological systems.

Finally, we can consider de anergy like

$$A=T_0\, dS_{gen} \qquad 8)$$

Results and Discussions

The thermodynamic formulation proposed in this work allows a quantitative description of ecological energy transformations by explicitly separating useful energy and degraded energy within ecosystem processes. From the energy quality perspective, the internal energy of the ecological system can be decomposed into organized useful energy (exergy) and degraded energy (anergy), as expressed previously in Equation (6). This decomposition provides a direct link between ecological energy flows and thermodynamic irreversibility, since anergy production is directly associated with entropy generation through irreversible metabolic processes (Equation 8). In ecological systems, this degradation of energy quality explains the progressive decrease of available energy along trophic levels and the continuous dissipation required to sustain biological organization. Within this framework, emergy represents the cumulative energy historically required to construct and maintain ecosystem structure. Because all energy transformations ultimately produce both useful and degraded components, emergy can be expressed as the time integral of the total energy processed by the system:

$$Em = \int_0^t U dt = \int_0^t (E + A)dt \qquad 9)$$

This expression shows that emergy includes both the energy incorporated into ecological organization and the energy irreversibly degraded during metabolic and ecological processes. As a result, ecosystems with greater structural complexity require larger cumulative energetic investments over time. Transformity measures the energetic cost of producing useful energy at higher hierarchical levels and can therefore be defined as the ratio between cumulative emergy and useful energy:

$$Tr = \frac{Em}{E} \qquad 10)$$

highlighting that higher levels of ecological organization require progressively larger energy inputs due to the accumulation of irreversibly degraded energy. Ecosystem organization can be interpreted as a dissipative structure maintained far from thermodynamic equilibrium. In such systems, the irreversible degradation of energy sustains internal organization while producing entropy. In the present framework, the rate of anergy production is directly related to entropy generation as defined in Equation 8, linking ecological dissipation with thermodynamic irreversibility. Because energy transformations occur through metabolic pathways and trophic interactions, the capacity of the ecosystem to dissipate energy depends not only on the incoming energy flux but also on the structural organization of the system. This relationship can be expressed in equation 11, which, using the definition of anergy in Equation 8.

$$\frac{dA}{dT} = \phi(B).E_{in} = T_0\sigma \qquad 11)$$

Here B represents the structural organization of the ecosystem, expressed through the total amount of organized biomass. In ecological systems, biomass integrates several aspects of structure, including population density, trophic interactions, and metabolic network connectivity. As biomass increases, the number of available pathways for energy transformation expands, enabling more complex metabolic and ecological interactions. Within this framework, the dissipative capacity of the ecosystem is represented by the function, where k is a proportionality constant reflecting metabolic activity and environmental conditions, and α represents the structural scaling of energy dissipation with biomass.

Substituting this expression into the anergy production relation gives

$$\phi(B) = kB^{\alpha} \Rightarrow \frac{dA}{dT} = kB^{\alpha}E_{in} \qquad 11)$$

which shows that the rate of anergy generation depends on both the incoming energy flux and the structural state of the ecosystem. As biomass increases, additional metabsolic pathways and trophic interactions enhance irreversible transformations, leading to greater entropy production and energy degradation. Ecosystem development can therefore be interpreted as the progressive emergence of structures capable of dissipating larger environmental energy flows while maintaining biological organization. This formulation provides a quantitative ecological interpretation of Prigogine's dissipative structures, where ordered organization is sustained through continuous energy degradation under non-equilibrium conditions.

From these considerations, a thermodynamic tendency for ecological systems can be proposed. As structural capacity for energy dissipation increases, the temporal evolution of anergy satisfies

$$\frac{d^2A}{dt^2} \geq 0 \qquad 12)$$

Conclusion

The thermodynamic formulation presented here provides a quantitative framework for describing ecological energy transformations using concepts from non-equilibrium thermodynamics. By linking anergy production with entropy generation, ecological processes can be expressed through measurable variables such as biomass, metabolic potential, exergy, anergy, and entropy production. Within this framework, the ideas of Howard T. Odum-particularly emergy and transformity—acquire a direct thermodynamic interpretation, describing the cumulative energetic investment required to build and maintain ecological structure across trophic levels. At the same time, ecosystem organization can be interpreted as a dissipative structure in the sense proposed by Ilya Prigogine, where biological order is sustained through irreversible energy degradation. Overall, this approach connects classical ecological energetics with non-equilibrium thermodynamics, providing a consistent basis for understanding hierarchical organization in ecosystems and the cumulative energetic cost required to sustain ecological complexity.

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