Postprint: Research on Non-Monetary Accounting of Ecosystem Service Functions

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Abstract

Distinct from monetary value accounting methods, environmental accounting approaches based on ecological thermodynamics conduct environmental accounting from a physical quantification perspective, aiming to transcend most economic methods grounded in anthropocentric frameworks. The new methodological framework further emphasizes the value of ecological services beneficial to both humans and ecosystems, that is, without neglecting the service functions provided by nature that are unrelated to human welfare. This paper reviews the theoretical foundations of ecological thermodynamics-based environmental accounting, reinterprets socio-economic systems from an intrinsic value perspective, and clarifies at a deeper level that current natural assets and ecological services are actually the effort and outcome of ecosystems in resource utilization, whose past ecological processes have undergone long-term trial-and-error and optimization. Through a case study of U.S. forest ecosystem service functions, it demonstrates the similarities and differences between ecological thermodynamics-based ecosystem service accounting methods and market value accounting methods based on willingness to pay, and proposes six steps for using the emergy method to account for ecosystem service functions. Finally, in response to recent improvements in the emergy method, four development prospects are presented: 1) The continuous updating of emergy baselines consolidates the foundation for non-monetary accounting of ecosystem service functions; 2) Numerous existing emergy analysis application cases in ecological assets and ecosystem service functions can provide methodological references and possibilities for comparison in future research; 3) The root of differences between monetary and non-monetary values of ecosystem service functions lies in the shift from anthropocentrism to ecocentrism in environmental ethics; 4) Studying ecosystem service functions from an ecological thermodynamics perspective establishes the possibility of proposing environmental taxes from an energy perspective. This study recommends adopting a dual accounting method, i.e., similar to the approach used in financial accounting, using energy to record

environmental liabilities and establishing a monetized balance sheet to illustrate economic conditions and the contribution of the environment to economic production.

Full Text

Preamble

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A Review of Non-Monetary Valuation of Ecosystem Services
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Abstract

Governments use money-based accounting systems of their national economies to calculate macroeconomic indicators such as Gross Domestic Product, Gross National Product, and Per Capita Income. Over the last few years, in response to the perceived lack of comprehensiveness of such accounting systems, more attention has been placed on the economic use and evaluation of ecosystems. Methods for calculating the value of ecological services are attracting interest as an instrument to convert the non-monetary values of the environment into real monetary thinking. The scientific discussion on methods to estimate these values is still embryonic. In several cases, the values of environmental services seem to be used arbitrarily for economic-based instruments, such as charging entrance payments to visitors and establishing a value for ecosystem services and natural capital.

This study summarizes the theoretical basis of environmental accounting based on ecological thermodynamics and reinterprets socio-economic systems from the perspective of donor-side value. Emergy—the total amount of solar equivalent energy invested by the environment in support of a given process—is suggested as a scientific measure of the direct and indirect work performed by the biosphere. Within such a "donor-side" perspective, the value of a resource relies on the effort needed for its production and delivery over a "trial and error" process that ensures optimization of resource use. Finally, based on improvements in recent emergy methods, four development perspectives are given: (1) the continuous updating of emergy benchmarks reinforces the foundation of non-monetary accounting of ecosystem service functions; (2) there have been large numbers of emergy analyses of ecological assets and ecology; (3) the difference between monetary and non-monetary values of ecological service functions lies in the transfer of environmental ethics from anthropocentric to ecocentric perspectives; and (4) the ecological perspective suggests that it is necessary to study the relationship between eco-service function and ecological value. From the thermodynamic perspective, the study of ecological service functions establishes the possibility of proposing environmental taxes. This study suggests both monetary and non-monetary accounting approaches could be used to quantitatively account for natural capital without relying solely on financial tools based on human preferences and fluctuating market dynamics.

Keywords: ecosystem services; emergy; non-monetary accounting method; monetary accounting method; pricing

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Introduction

Methods for environmental accounting have gradually entered researchers' field of vision and quickly become instrumental for studying the reserve value of natural resources. The Economics of Ecosystems and Biodiversity (TEEB), an international project completed in 2010, attempted to evaluate the contributions of ecosystems and biodiversity in monetary terms within the framework of productive economic systems. The System of Environmental-Economic Accounting (SEEA), proposed in the late 20th century, incorporates environmental factors into national accounting by treating environmental costs as direct or indirect costs or benefits in economic accounting. Many countries have attempted to calculate "green GDP" by deducting resource depletion costs and environmental degradation costs from conventional GDP. However, due to difficulties in implementation and immature practical experience, these approaches often fail to achieve expected goals.

Neoclassical economics, founded on the "Marginal Revolution," shifted focus from production means to market dynamics. Neoclassical economist Solow completely removed land from the economic production function, asserting that natural work could be substituted by manufactured capital. Georgescu-Roegen refuted this claim, arguing that economics is constrained by thermodynamic limits. At this point, valuation of environmental contributions to the economy diverged into two camps: biophysical assessment methods (such as life cycle analysis) and ecological economics. Since neoclassical principles decouple economy from environment, integrating natural resource assets and ecosystem services into human economic systems has become one of the most important questions in ecological economics research.

Typical methods that conduct environmental accounting primarily from a material measurement perspective include ecological footprint analysis, material flow analysis (calculating direct and hidden material inputs from nature to the economic system), embodied energy accounting (cumulative energy consumption), environmental impact assessment methods for economic process emissions, greenhouse gas accounting, and emergy analysis. These methods reflect the true load of human activities on natural resources and the environment, becoming important tools for guiding and evaluating environmental performance and sustainable development. Their focus is treating all parts of Earth' s ecosystem as a functional whole containing structure and process, with human socio-economic systems embedded as only one component. This framework enables detailed accounting of how various species obtain natural resources and services, and reveals how to maximize output efficiency of both ecosystems and economic systems.

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1. Theoretical Basis of Environmental Accounting Based on Ecological Thermodynamics

Emergy analysis has sustained attention in environmental accounting due to its unique theoretical and methodological system. Developed in the 1980s by renowned American ecologist and systems energy analysis pioneer H.T. Odum—building upon his brother P. Odum' s frustration with the inability to intuitively express energy ecology and drawing on electrical circuit principles from physics—emergy theory represents a new systems analysis approach. It measures from the perspective of Earth' s biosphere energy movement, using solar emergy to express all energy consumed in forming or producing a resource or product, and establishes general system sustainability evaluation indicators.

H.T. Odum began in-depth research on ecosystem energetics in the 1950s, proposing novel concepts and pioneering ideas such as energy systems and energy quality, first linking energy flow with economic flow. The term "emergy" was coined in 1983 by visiting Australian scholar David Scienceman, who combined "embodied energy" into a new word. For a period, emergy researchers capitalized it as "eMergy" to distinguish it from "embodied energy." H.T. Odum subsequently established emergy theory and solar transformity concepts. The evolution from energy analysis to emergy analysis represents a major theoretical and methodological leap.

In his 1988 *Science* article "Self-Organization, Transformity, and Information," Odum elaborated on the relationship between emergy and energy quality, energy hierarchy, and other concepts. His 1996 book *Environmental Accounting: Emergy and Environmental Decision Making* is considered the first systematic representative work in emergy research, with milestone significance. In this work, Odum identified natural capital and ecosystem services as the true source of wealth—the donor-side perspective—contrasting with the prevailing receiver-side view that only labor and economic capital create wealth.

This perspective connects living and non-living components into a functional whole that performs ecological functions through energy, reflecting ecological relationships, structural characteristics, and connection patterns. E.P. Odum viewed the entire biosphere as the largest living organism—an integrated organic system composed of all organisms and Earth' s environment. This reinterpretation of socio-economic systems from a donor-value perspective clarifies that natural assets and ecological services are actually the effort and result of ecosystem resource use, with ecological processes undergoing long-term trial and error and optimization.

Compared to other environmental accounting methods, emergy analysis has distinct advantages: it converts all incomparable items—including different energy types, materials, information, labor, and services—into a unified dimension (solar equivalent joules), providing a new approach for environmental load calculation and environmental-economic performance evaluation. Emergy theory is based on material and energy flow laws within the biosphere, grounded in energetics principles and systems ecology. In reflecting the true value of natural resources and ecological services, emergy is more persuasive. Its detailed analysis of material flows and energy transfers also makes it an important tool for system analysis and evaluation.

From the donor-side perspective, energy is defined as the total available energy required to directly and indirectly support a process and produce output products or services, typically normalized to solar equivalent joules (though some studies use cosmic radiation). All renewable and non-renewable, local and imported energy flows are inventoried and converted to solar equivalent joules through unit emergy values (UEVs). This allows unified accounting of all energy input flows to a process, followed by calculation of relevant performance indicators. In evaluating economies, the relationship between energy supply and economic performance is measured by the ratio of total energy use to Gross Domestic Product (GDP), expressed in monetary units. This emergy-to-money ratio represents the total emergy investment required to create one unit of monetary wealth and is used to convert monetary inputs associated with labor and services into emergy units.

Emergy analysis is considered a bridge between ecology and economics, opening new quantitative research methods for comprehensive analysis of various ecological flows in eco-economic systems. It provides a common scale for measuring and comparing material and value flows, enabling quantitative analysis of the entire natural and human socio-economic system, the true value of resource-environment and economic activities, and their relationships. This is significant for coordinating ecological environment and economic development, scientifically evaluating and rationally utilizing natural resources, formulating economic development policies, and implementing sustainable development strategies.

From an ecological thermodynamics perspective, natural assets and ecological service functions are generated through the interaction of high-quality energy (e.g., fossil fuels) and low-quality energy (e.g., solar radiation) in convergent and divergent processes. The role of these processes is to accelerate energy flow and release new storage capacity—for example, transforming petroleum into electricity and transportation services, minerals into infrastructure and machinery, and machinery and ecological services into education. The thermodynamic value of ecological service functions lies in enhancing the stability of energy transmission processes. To prevent or delay resource depletion, ecosystems replant trees after logging, return straw to fields to maintain soil organic matter and nutrients, and recycle materials to ensure the stability of the energy base.

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2. Method for Accounting Ecological Service Functions Based on Ecological Thermodynamics

Definitions of ecosystem services vary among organizations and researchers. The Millennium Ecosystem Assessment (MEA) defines them as benefits people obtain from ecosystems, focusing on human values and preferences. The MEA report identifies four categories: provisioning, regulating, supporting, and cultural services. These involve providing products to humans, regulating ecosystems that humans depend on, supporting systems that provide services, and enhancing cultural and recreational experiences. However, this receiver-side perspective overlooks ecosystem services that are not directly used by humans.

Ecosystem services research should consider not only services with market value but also those without market value. Ecological price accounts for the total societal benefits of ecosystem services. Emergy analysis converts ecosystem service emergy into monetary value through the emergy-to-money ratio (national emergy consumption divided by GDP), enabling ecological price accounting. Emergy analysis views a region' s GDP as resulting from local renewable resources, non-renewable resources, and imported/exported products and services. Through unified accounting of all regional inputs using solar emergy, ecosystem service functions and the overall economic system can be integrated into a complete accounting framework, allowing balanced comparison of ecological service functions with total economic value in either energy or monetary units without overvaluation.

Ecological price more accurately assesses the energy required for ecosystem services from a donor-value perspective—that is, evaluating multiple ecosystem services from the same land area rather than simply summing all values through traditional willingness-to-pay methods. This involves the donor-side principle in ecosystem service assessment: quantifying the value of ecosystem services provided to humans. Emergy methods coordinate biological materials provided by ecosystems for people, making it crucial to integrate ecosystem services into economic systems for unified accounting. If ecosystem service degradation becomes limiting to economic activity, maintenance costs for natural capital restoration will far exceed preventive maintenance costs before degradation occurs.

Brown and Campbell' s calculation of U.S. forest ecosystem services provides preliminary comparison between emergy-based and monetary methods. Their results show that forests' ecological value ranks first, not water supply, and that ecological value is 2.5 times market value. The largest value provision is recreation, while ecosystem services without market value are 1.7 times those with market value.

Emergy, emergy-converted "ecological value," and monetary valuation of U.S. forest ecosystem services

The table demonstrates that for services distant from market pricing, the difference between ecological value and market value is greater. For services with markets (e.g., provisioning services), values align more closely with market value, except for water supply. Services like mineral and fossil fuel extraction show ecological values about 10 times their monetary values, reflecting society' s enormous benefits from low-priced minerals and fuels. Services without market pricing (e.g., air purification) have ecological values significantly higher than market values, which may change as public sensitivity to air pollution increases.

Emergy, ecological value, and market value of U.S. National Forest System services (2005)

Current emergy research has developed accounting methods for different ecosystem services. We propose six steps for ecosystem service accounting using emergy methods: (1) Conduct emergy accounting for the study area using the latest emergy benchmarks; (2) Calculate the emergy-to-money ratio coefficient for converting cultural services valued in local currency; (3) Account for ecological capital in the study area, focusing on product-based provisioning services; (4) Develop micro-models for different ecosystem service functions to determine emergy inputs required for each key service; (5) Assess monetary amounts directly or indirectly paid for natural services in existing markets (e.g., stormwater retention fees, carbon storage in carbon markets, watershed protection fees, pollutant disposal fees) to quantify ecological value through alternative or shadow pricing; (6) Integrate ecosystem service values into the study area' s existing socio-economic system, developing results into standard spreadsheets for evaluators to verify and validate ecosystem service assessments.

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3. Criticisms of the Emergy Method and Recent Improvements

Like most biophysical environmental accounting methods, the key to emergy' s systematic measurement using unified units lies in the accuracy of ecological asset stocks and emergy transformities. These issues constituted early debates between emergy researchers and traditional economists regarding ecological thermodynamics and uncertainty. Most problems have been resolved over the past decade, though their initial articulation was necessary and stimulated further methodological improvements. Many issues raised by Baksheesh—such as uncertainty, indicator sensitivity, and methodological choices for quantification—also apply to other holistic methods like life cycle assessment and material flow analysis. Below we address core issues in non-monetary accounting of ecosystem services.

3.1 Continuous Updating of Emergy Benchmarks Consolidates the Foundation of Non-Monetary Accounting

The main emergy flows driving the geobiosphere are crucial for emergy accounting as they serve as references for other flows. The system boundary extends from Earth' s surface to 10,000 meters above and below. This benchmark' s prototype can be traced to Odum' s initial inclusion of only solar energy driving Earth' s ecosystems. Subsequent developments incorporated tidal power and geothermal energy, converting them to equivalent solar emergy.

Odum' s 2000 calculation yielded 9.44×10^2 seJ/a, which was later updated to 15.83×10^2 seJ/a using better data. Because emergy transformities are directly related to the benchmark, using different benchmarks requires corresponding conversion coefficients for transformity values. Campbell (2010) adopted Brown and Ulgiati' s recalculated tidal energy value, while Brown and Ulgiati (2016) used advanced satellite mapping data and Monte Carlo simulation to recalculate global geothermal energy, considering uncertainties in mantle-crust distribution.

Comparison of three benchmark calculations for annual emergy contributions to global processes

The results yield an emergy baseline of approximately 15.20×10^2 seJ/a. Monte Carlo simulation addresses uncertainty in emergy analysis. Beyond value changes, emergy benchmarks have various names, including "geobiosphere emergy baseline" (GEB). Brown, Ulgiati, and Campbell (2016) published updated calculations with values around $11.9\text{–}12.1\times10^2$ seJ/a, which could be named GEB2016 given future revision possibilities.

The unit "seJ" (solar equivalent joules) is used because tidal and geothermal energies differ fundamentally from solar radiation. Regardless of which benchmark is adopted, the specific value is less important than consistent application, as results are benchmark-relative. Ulgiati et al. liken the emergy benchmark to altitude in geography—a reference baseline. However, researchers must select one benchmark and carefully identify which values references use. Like fundamental constants in various disciplines, benchmarks update with new knowledge. If all emergy researchers reference a unified benchmark, studies become more comparable.

3.2 Numerous Emergy Analysis Cases Provide Methodological References

Emergy research has advanced rapidly in recent years, covering theory, methodology, benchmarks, dynamics, and uncertainty. Applications span multiple scales and systems: urban/regional ecosystems, agricultural systems, eco-industrial parks, nature reserves, tourism, and national-level analyses.

Integration with GIS, life cycle assessment (LCA), and ecological footprint methods has received attention. Odum first analyzed the U.S., Switzerland, and other countries, establishing foundations for regional emergy research. Liu Gengyuan and Brown (2014) updated national emergy accounting data for world countries, calculating renewable energy and updating transformities to improve accuracy, providing globally comparable reference values for ecosystem service emergy assessment.

Existing research areas of emergy analysis

3.3 Ethical Shift from Anthropocentrism to Ecocentrism

Increasingly, people recognize anthropocentrism as a major cause of environmental destruction. Forest degradation exemplifies this: anthropocentrism provides reasons for logging (building houses) while ignoring forests' intrinsic value and ecological services. Many environmental protection concepts have emerged to counter anthropocentrism, focusing on humans as environmental stewards rather than special beings, emphasizing other organisms in the global environment. This management role reflects a shift from anthropocentrism to ecocentrism.

The concept of "stewardship" has philosophical and ethical dimensions, viewing humans as ecosystem guardians and part of integrated nature. This reflects environmental ethics' evolution. Emergy' s ecological philosophy is holistic: it opposes anthropocentrism by positioning humans as just one component. Organization levels mean components can combine to produce greater functional wholes with emergent properties not present at lower levels—characteristics that cannot be reduced to component traits. This irreducibility calls for environmental ethics attention.

3.4 Thermodynamic Perspective Establishes Possibility for Energy-Based Environmental Taxes

Bimonte and Ulgiati identify a "new scarcity" : ecosystem support systems are increasingly insufficient. If resource development continues without considering environmental integrity, degraded ecosystems become unable to provide basic services. They propose an emergy-based tax system for environmental integrity, using the Environmental Sustainable Index (ESI) to penalize development patterns that use less environmentally benign technology or fewer renewable resources. This tax treats the ecological environment maintaining economic activity as a form of capital, with tax revenue restoring the ecosystem' s capacity to support economic development.

This approach, similar to Barnes' idea of returning wealth to stakeholders, applies to current free-market systems. It enables comprehensive assessment of regional ecosystem services and economic inputs for environmental policy implementation. Tax purposes extend beyond limiting single resource efficiency or emissions to overall environmental integrity protection and restoration, slowing ecological asset depreciation through investment in ecological restoration.

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4. Conclusion

This study systematically reviews the theoretical basis and methodological framework for non-monetary accounting of ecosystem services based on ecological thermodynamics, summarizing two key characteristics: (1) Capital accounting is based not on human preferences but on environmental support requirements for eco-economic systems within defined spatiotemporal scales; (2) It provides more scientific accounting for inputs that are difficult to replace once depleted. Though these low-quality, dispersed inputs are rarely captured by market dynamics, they are crucial as they reflect biosphere value.

Emergy methods connect ecological and economic systems by revealing ecological connotations for fairer ecological capital pricing and natural capital restoration through environmental taxes. This natural system perspective is overlooked in conventional economic dynamics. Emergy methods can determine ecosystem services' "biosphere value," complementing existing monetary valuation. Given current limitations in ecological asset and ecosystem service accounting, we recommend a dual accounting approach: recording environmental liabilities in energy units while establishing a monetized balance sheet illustrating economic conditions and environment' s contribution to production—creating a new financial system that returns wealth to all stakeholders, including nature.

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Note: Figure translations are in progress. See original paper for figures.