# The HEROS Framework: A Methodological Approach for Assessing Immovable Cultural Heritage as an Active Component of the One Health System

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# The HEROS Framework: A Methodological Approach for Assessing Immovable Cultural Heritage as an Active Component of the One Health System

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**Abstract**

Immovable cultural heritage—archaeological sites, historic buildings, and culturally significant infrastructure—has traditionally been approached through conservation, material preservation, and identity-based perspectives. However, the evolution of heritage theory and the emergence of systemic paradigms such as One Health call for its reinterpretation as an active component within interconnected human, animal, and environmental systems. Although One Health recognizes the interdependence of these domains, no operational framework currently assesses the functional contribution of immovable cultural heritage. This study develops a formal methodological framework that operationalizes immovable cultural heritage as a functional element within the One Health system. The framework integrates environmental, animal, and human health domains through structured indicators, mathematical formalization, and internal validation procedures. It explicitly incorporates the coexistence of tangible and intangible heritage dimensions, acknowledging their embedded socio-ecological relationships. The plausibility and coherence of the framework is validated against established scientific literature, environmental assessment models, and foundational One Health principles. Results demonstrate that the proposed approach enables systematic, reproducible, and domain-complete assessment of immovable cultural heritage within the One Health paradigm, overcoming methodological fragmentation and supporting integration with sustainability analysis, environmental governance, resilience planning, and long-term socio-ecological stability.

**Keywords:** One Health; cultural heritage; intangible cultural heritage; methodological framework; environmental health; sustainability; resilience; heritage assessment; ecosystem health

## 1. Introduction

The concept of cultural heritage has undergone a profound transformation over the past century, evolving from a narrow focus on the preservation of exceptional monuments and historical artefacts toward a broader systemic understanding that encompasses places, landscapes, infrastructures, and associated cultural practices [1]. Initially framed primarily in terms of material authenticity and historical continuity, immovable cultural heritage, which includes archaeological sites, as well as historic buildings and significant historical infrastructures, was treated as an object of preservation whose value resided in its physical fabric and its capacity to transmit historical information across generations. Over time, this perspective expanded to recognize that heritage cannot be reduced to its material substrate alone. Instead, it constitutes a dynamic interface between human societies and their environments, shaped by continuous interaction, reinterpretation, and use.

This transformation has been accompanied by the recognition that immovable cultural heritage is inseparable from its intangible dimension. Even when expressed through material structures,

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heritage embodies systems of knowledge, symbolic meanings, practices, and cultural relationships that persist through transmission and use. These intangible dimensions include ecological knowledge, spatial practices, ritual uses, and culturally embedded interactions with specific places. In fact, according to According to the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage, cultural heritage includes "practices, representations, expressions, knowledge and skills […] transmitted from generation to generation and constantly recreated by communities, providing them with a sense of identity and continuity" [2]. As a result, immovable cultural heritage must be understood not as a static material object, but as a material and symbolic product of a social-ecological system in which material and intangible components coexist and interact continuously [3]. This integration becomes particularly evident in cultural landscapes, sacred sites, and historically significant natural locations, where environmental features, such as forests, lakes, or geological formations, acquire enduring symbolic, cultural, and functional significance. In such cases, the conventional distinction between "natural heritage" and "cultural heritage" becomes analytically inadequate, as the significance of the site emerges from the interaction between physical environmental features and human cultural interpretation and use.

In parallel with this conceptual evolution, the rationale for heritage protection has also shifted. Initially motivated by the preservation of historical testimony and artistic value, heritage protection is now increasingly linked to broader societal goals, including sustainability, resilience, environmental stewardship, and community wellbeing [4,5]. This shift reflects the recognition that heritage structures and sites are not isolated artefacts, but embedded components of larger environmental and social systems. Immovable cultural heritage interacts with ecological processes, contributes to landscape stability, mediates human–environment relationships, and influences patterns of land use and environmental management. These interactions position heritage within the broader domain of environmental governance, rather than solely within cultural policy.

The emergence of the One Health framework could provide a yet unexplored applicative context for this shift. One Health is defined as an integrated approach, that recognizes the interdependence between human health, animal health, and environmental health, emphasizing the need to address complex systemic risks that arise from interactions between these domains [6]. Originally developed in response to zoonotic diseases and environmental health risks, One Health has expanded to encompass broader considerations of ecosystem stability, environmental sustainability, and the governance of human–environment interfaces [7]. Despite its systemic scope, current One Health assessment methods do not include cultural heritage as an explicit component, and no operational framework exists to evaluate how immovable cultural heritage contributes to environmental stability, animal–human interfaces, or human health and resilience. In fact, until now, the relations between cultural heritage and one health have been limited, considering the health conditions of workers and the public in museum settings [8,9] and the subjective well-being, in terms of physical and mental health, in relation to cognitive decline and the mitigation of stress conditions [10,11].

This absence represents a significant knowledge and methodological gap. Immovable cultural heritage sites frequently occupy ecologically significant locations, influence environmental management practices, and mediate interactions between human populations and ecosystems. Moreover, their associated intangible dimensions, such as ecological knowledge systems, land-use traditions, and culturally embedded environmental practices, can shape behavioural patterns and environmental outcomes. Without a methodological framework capable of operationalizing these interactions, the potential role of immovable cultural heritage within the One Health system remains unassessed and unquantified.

Therefore, this study aims to develop and formalize a methodological framework that enables a systematic assessment of immovable cultural heritage as an active component of the One Health system. This work introduces the HEROS framework (HERitage One Health System), a structured methodological model designed to support a clearer representation of the role of immovable cultural heritage within interconnected environmental, animal, and human health domains under the One Health perspective. The framework explicitly recognizes that immovable cultural heritage cannot be

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separated from its associated intangible dimensions, which include knowledge systems, symbolic meanings, and culturally embedded practices that mediate interactions between human societies and their environments. By defining a generalized system of indicators and mathematical structure of domain interactions, while establishing internal validation procedures supported by consistency with existing scientific knowledge, the HEROS framework provides a reproducible and operational tool for assessing immovable cultural heritage within the One Health paradigm. In doing so, it enables the integration of cultural heritage into environmental health assessment, sustainability analysis, and environmental governance, and offers a methodological basis for evaluating the contribution of heritage sites to the stability, resilience, and long-term viability of social-ecological systems.

## 2. Materials and Methods

### *2.1. Conceptual Foundation of the HEROS Framework*

The HEROS framework was developed to operationalize the assessment of immovable cultural heritage as an active component of the One Health system. The conceptual foundation of the framework is based on the recognition that immovable cultural heritage, including archaeological sites, historic buildings, and culturally significant infrastructures, constitutes a persistent interface between human populations, animal communities, and environmental systems. These heritage sites are not isolated artefacts, but embedded components of social-ecological systems, in which material structures, environmental processes, biological communities, and culturally mediated human behaviours interact continuously over time.

The framework is grounded in the core structure of the One Health paradigm, which identifies environmental health, animal health, and human health as interdependent domains connected through shared environmental interfaces. While primarily focusing on biological and environmental determinants, the One Health framework do not explicitly account for the role of immovable cultural heritage as a structural and functional component within these systems. Nonetheless, immovable cultural heritage influences environmental stability, mediates human–animal interactions, and shapes human exposure patterns through its physical properties, spatial configuration, environmental integration, and associated cultural practices. These influences operate through both material and intangible dimensions. Moreover, immovable cultural heritage sites frequently serve as ecological interfaces where interactions between human populations and animal species occur, either through habitat provision, spatial overlap, or mediated contact. In parallel, the intangible dimension of immovable cultural heritage, which includes the systems of knowledge, symbolic meanings, practices, and behavioural patterns associated with specific sites, influence how human populations interact with heritage environments, regulate patterns of access and use, and shape environmental and habits over time. Thus, intangible heritage contributes to the stability of social-ecological systems by transmitting ecological knowledge, reinforcing spatial and environmental continuity, and regulating human–environment interactions through culturally embedded behavioural frameworks. As a result, the material and intangible dimensions of immovable cultural heritage function as a unified system that influences environmental, animal, and human health domains simultaneously.

Based on this conceptual foundation, the HEROS framework defines immovable cultural heritage as a multidomain interface within the One Health system, capable of influencing environmental stability, animal interface dynamics, and human health exposure and resilience. The framework operationalizes these interactions by identifying domain-specific pathways through which immovable cultural heritage contributes to the structure and function of social-ecological systems. These pathways are formalized through a structured system of indicators, enabling systematic and reproducible assessment.

The framework adopts a domain-based structure aligned with the One Health paradigm, defining three primary domains: environmental domain, animal domain, and human domain. Each domain represents a distinct but interconnected dimension of the One Health system. The environmental domain captures the influence of immovable cultural heritage on environmental

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structure, ecological stability, and landscape continuity. The animal domain captures the role of heritage sites as ecological interfaces that may influence habitat availability and mediate interactions between human populations and animal species. The human domain captures the influence of heritage sites on exposure pathways, behavioural regulation, and resilience within human populations.

The HEROS framework further agrees on the fact that the separation between natural and cultural heritage sites, being primarily administrative rather than functional [12]. Many immovable cultural heritage sites are embedded within environmental systems that possess ecological, symbolic, and cultural significance simultaneously. Natural sites with recognized cultural significance, such as sacred landscapes or historically significant natural features, function as immovable cultural heritage within the HEROS framework because their role in shaping human–environment relationships is mediated through cultural recognition and interaction. Conversely, built heritage sites often function as environmental structures influencing ecological processes and biological interactions. This functional perspective enables the HEROS framework to integrate both cultural and natural heritage contexts within a unified methodological system, without relying on rigid categorical distinctions.

By defining immovable cultural heritage as a structural component of social-ecological systems and formalizing its interaction pathways within the One Health paradigm, the HEROS framework establishes the conceptual basis for the development of a quantitative and reproducible assessment methodology. The subsequent sections define the domain structure, indicator system, and mathematical formalization that enable operational implementation of the framework.

### *2.2. Ontological Structure of the System and Operational Domain Distinction*

Adopting a broad perspective, the system addressed by the HEROS framework consists fundamentally of two primary components: the abiotic component and the biotic component. The abiotic component includes all non-living physical structures and environmental resources, while the biotic component includes the entirety of the biosphere, encompassing all living organisms and their interactions. Within this biotic component, humans and animal populations should not constitute ontologically separate domains, but specific subsets of the biosphere.

The distinction between environmental, animal, and human domains adopted in the HEROS framework derives from the need of defining an operational structure, that can be applied to the One Health paradigm, which explicitly emphasizes the interdependence between environmental conditions, animal health, and human health, with the ultimate goal of protecting human health through the preservation of environmental integrity and animal system stability. As such, the One Health framework introduces a functional distinction between these domains based on applied health objectives, rather than on fundamental ecological separation.

From a strictly ecological and thermodynamic perspective, this distinction is fictious, being inherently anthropocentric, insofar as it assigns analytical priority to human health outcomes and identifies environmental and animal system stability as conditions necessary to sustain human health [13]. Conversely, human communities constitute a subsystem of the biosphere and are subject to the same energetic, material, and informational constraints that govern all biological systems. The biosphere itself operates as an integrated thermodynamic system embedded within the abiotic environment, and its stability cannot be fully understood through anthropocentric classification alone.

Despite this ontological limitation, the domain-based structure of the One Health paradigm provides a practical and operational analytical framework, that enables the identification and quantification of interaction pathways relevant to system stability and health outcomes. For this reason, the HEROS framework adopts the environmental, animal, and human domain distinction as a first-order operational approximation, while explicitly recognizing that these domains represent interacting components within a unified biophysical system.

Within this operational structure, the environmental domain includes both abiotic components and those biotic components not explicitly identified within the One Health perspective. With this

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respect, animal and human domains are considered functionally distinguished subsets of the biosphere that are emphasized due to their specific role in One Health analysis. This formulation preserves compatibility with One Health analytical practice while maintaining conceptual consistency with system ecology and donor-side accounting principles, in which all system components are ultimately governed by unified energetic, material, and informational dynamics.

### *2.3. Definition of System Domains and Interaction Pathways*

The HEROS framework operationalizes the role of immovable cultural heritage within the One Health system by defining three primary domains of interaction: the environmental domain, the animal domain, and the human domain. These domains correspond to the three fundamental components of the One Health paradigm and represent distinct but interconnected dimensions through which immovable cultural heritage can influence the structure and function of social-ecological systems. Each domain is defined in terms of its functional relationship with immovable cultural heritage and the mechanisms through which heritage sites influence environmental stability, animal interface dynamics, and human health and resilience.

#### 2.3.1. Environmental Domain

The environmental domain represents the influence of immovable cultural heritage on environmental structure, ecological stability, and landscape continuity. Immovable cultural heritage sites are spatially fixed and often persist over long temporal scales, contributing to the stabilization of land-use patterns and environmental configuration. Their physical presence influences environmental processes including land-use continuity, surface stability, vegetation distribution, microenvironmental conditions, and ecological connectivity.

Heritage structures and sites may act as long-term stabilizing elements within landscapes, reducing the likelihood of disruptive land transformation and contributing to the persistence of environmental configurations. In addition, immovable cultural heritage sites frequently form part of historically stable landscape systems, including cultural landscapes, archaeological complexes, and historically managed environments. These characteristics enable heritage sites to contribute to environmental continuity and structural stability within social-ecological systems.

The environmental domain within the HEROS framework therefore captures pathways through which immovable cultural heritage contributes to environmental stability, ecological interface structure, and landscape persistence. These pathways operate through physical stabilization, environmental integration, and spatial continuity mechanisms.

#### 2.3.2. Animal Domain

The animal domain represents the role of immovable cultural heritage sites as ecological interfaces that may influence interactions between animal populations, environmental systems, and human populations. Immovable cultural heritage sites may provide physical structures, environmental niches, or spatial configurations that influence habitat availability, species distribution, and patterns of animal movement. This may occur through direct habitat provision, indirect environmental stabilization, or spatial overlap between animal populations and heritage sites.

In addition to habitat-related mechanisms, heritage sites may also mediate interfaces between animal and human populations. Because immovable cultural heritage sites are often accessible to human populations and located within shared environments, they may function as spatial points of interaction between human and animal communities. These interactions may influence exposure pathways, ecological dynamics, and environmental interface conditions.

The animal domain within the HEROS framework therefore captures pathways through which immovable cultural heritage sites contribute to animal–environment interfaces and animal–human

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interaction dynamics. These pathways operate through habitat interface mechanisms, ecological integration, and spatial interaction processes.

#### 2.3.3. Human Domain

The human domain represents the influence of immovable cultural heritage sites on human exposure patterns, behavioural regulation, and resilience within social-ecological systems. Immovable cultural heritage sites influence human populations through both material and intangible pathways. Material pathways include physical accessibility, spatial configuration, environmental integration, and environmental exposure conditions associated with heritage sites. These characteristics influence how human populations interact with heritage environments and may shape exposure to environmental, biological, and physical factors.

Intangible pathways include the cultural, symbolic, and behavioural dimensions associated with heritage sites. These include knowledge systems, spatial practices, symbolic meanings, and culturally mediated behavioural norms that regulate human interaction with heritage environments. These intangible dimensions influence patterns of use, environmental behaviour, and long-term continuity of human–environment relationships.

Immovable cultural heritage sites may also contribute to resilience within human populations by reinforcing environmental continuity, spatial orientation, and cultural stability. Through their persistence and cultural significance, heritage sites function as stable reference points within social-ecological systems, supporting behavioural continuity and environmental familiarity.

The human domain within the HEROS framework therefore captures pathways through which immovable cultural heritage influences human exposure patterns, behavioural regulation, and resilience. These pathways operate through environmental exposure mechanisms, spatial interaction processes, and culturally mediated behavioural frameworks.

#### 2.3.4. Domains Interaction Structures

Although defined separately for methodological clarity, the environmental, animal, and human domains are inherently interconnected. Immovable cultural heritage sites operate as shared interface structures within which environmental processes, animal communities, and human populations interact. Environmental stabilization may influence habitat conditions for animal populations, while animal presence may influence human interaction patterns and exposure pathways. Similarly, culturally mediated human behaviour associated with heritage sites may influence environmental management and ecological conditions.

The HEROS framework therefore treats these domains as components of an integrated system, in which immovable cultural heritage functions as a structural interface linking environmental, animal, and human health domains. This domain-based structure provides the operational foundation for the development of indicator systems and mathematical formalization described in the following sections.

Three primary domains were defined: environmental domain, animal domain, and human domain. The environmental domain includes interactions between heritage sites and ecological stability, land use continuity, and environmental processes. The animal domain includes the role of heritage sites as ecological interfaces that may provide habitats, influence species interactions, or mediate animal–human contact. The human domain includes exposure pathways, behavioural interactions, and resilience contributions associated with heritage sites. For each domain, interaction pathways were identified based on physical, ecological, and socio-cultural mechanisms

### *2.4. HEROS Framework Structure and Indicators System*

The HEROS framework operationalizes the role of immovable cultural heritage within the One Health system through a structured indicator system grounded in stock–flow formalism derived from system ecology. Within this formalism, the system is represented as a set of interacting stocks

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connected by flows governing the transfer, transformation, and dissipation of material, energetic, and informational resources. The indicator system is designed to quantify the state of system stocks, the magnitude of interaction flows, and the regulatory role of immovable cultural heritage within the integrated dynamics of the system.

Consequently, within the HEROS framework, indicators generally do not quantify the stocks or the nature of flows and their interactions. Instead, they support the structure and parameterization defining the functional relationships the governs the dynamics of the system, understood as Confined Ontic Open Systems (COOS), that are real physical systems that: (i) Exist as ontic entities, meaning they possess objective physical existence independent of observation; (ii) Are spatially confined, meaning they occupy a finite and identifiable region of space defined by physical or functional boundaries; (iii) Are thermodynamically open, meaning they exchange energy, matter, and information with their surroundings; (iv) Maintain their internal organization through continuous throughput of energy and matter, while undergoing irreversible dissipative processes governed by thermodynamic laws. Therefore, indicators act as control variables, that modulate the governing functions of stock dynamics, influencing system stability and availability dissipation rates. This formulation ensures full consistency with system ecology formalism, where system structure and boundary conditions determine flow behaviour and dissipation dynamics.

#### 2.4.1. System Ecology Foundations and Methodological Basis

Although The HEROS framework is grounded in the epistemological and methodological foundations of system ecology, which provides a physically consistent approach for representing complex systems in terms of interacting stocks, flows, and regulatory feedbacks. System ecology emerged from the convergence of thermodynamics, general systems theory, and ecological science, and provides a formal structure for analyzing systems whose behaviour is governed by the transformation and circulation of energy, matter, and information.

The origins of this approach can be traced to early developments in systems theory and thermodynamics. Köhler first demonstrated that physical systems in stationary states can be understood through structural relationships among interacting components rather than through linear cause–effect chains [14]. This perspective was further developed by Bertalanffy General Systems Theory and by Forrester's system dynamics, which introduced formal methods for representing system structure and temporal evolution using stock–flow diagrams and differential equations [15,16]. These representations allow complex systems to be modelled as sets of interacting state variables governed by resource flows and feedback mechanisms. This formal structure was subsequently extended to ecological systems by Howard T. Odum, who demonstrated that ecosystems and human-dominated systems can be described using unified energetic accounting principles [17]. This approach enables the physical quantification of system organization, persistence, and stability across both natural and human-modified environments.

Within this framework, systems are represented as networks of interacting stocks connected by flows of energy, matter, and information [18]. Stocks represent accumulated system components, while flows represent the transfer, transformation, or dissipation of resources. This representation provides a physically grounded method for quantifying system structure and dynamics. Importantly, system ecology recognizes information as a bio-physical resource that regulates system organization alongside matter and energy [19]. Informational structures contribute to system persistence by stabilizing interaction patterns and guiding system dynamics.

Recent work has extended this eco-physical perspective to immovable cultural heritage, demonstrating that heritage assets can be interpreted as persistent system components embedded within material, energetic, and informational flows. Heritage structures participate in urban metabolism through the accumulation of material and energetic resources and through the transmission of informational structures that regulate environmental interaction and social–ecological stability [20]. Their persistence contributes to the stabilization of environmental conditions,

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the modulation of resource flows, and the maintenance of informational continuity within social–ecological systems.

The HEROS framework adopts this system ecology perspective as its methodological foundation. Cultural heritage is treated as a persistent structural and informational component embedded within the broader system composed of abiotic and biotic stocks. Indicators are therefore not arbitrary descriptive variables, but operational representations of measurable state variables and resource flows governing system dynamics. This ensures that the framework remains physically grounded and compatible with thermodynamic accounting principles, ecological energetics, and emergy-based resource analysis.

2.4.2. Definition of System Stocks

Although Within the HEROS framework, system stocks represent persistent structural and informational components of the social-ecological system. These stock definitions are intentionally formulated at a generic level, in order to provide a universal methodological structure applicable across different heritage contexts, environmental conditions, and spatial scales. The explicit operational definition and quantification of each stock must therefore be specified during case-specific implementation, based on the physical, ecological, and cultural characteristics of the system under investigation. In this sense, the stock definitions provided here constitute generic state variables within a system, whose specific measurement and parameterization depend on the empirical context.

Adopting a broad perspective, the system consists of an abiotic and a biotic subsystem, that can be detailed through the quantification of their stocks, representing the pool of resources contained in each subsystem. The stocks, then, are connected through flows, that are used to represent the temporal variability of stocks, and processes, that are interactions among flows. For sake of simplicity, we will refer to the stocks contained in each subsystem in general terms as abiotic and biotic environmental stocks. We will maintain this level of language generalization and simplification for coherence, while reminding the underlying complexity of the representation.

The abiotic environmental stock, $A(t)$, represents the non-living physical substrate of the system, including geological structures, physical environmental configuration, and abiotic resource reservoirs. The biotic stock, $B(t)$, represents the biosphere component of the system, including all living organisms and their interactions with the abiotic environment.

Within this biotic stock, human and animal populations emerge as functionally distinguishable subsets. These subsets do not constitute ontologically independent stocks, but rather represent specific partitions of the biotic stock identified for operational purposes within the One Health framework. Formally, the biotic stock may be expressed generically as:

$$B(t) = B_{animal}(t) + B_{human}(t) + B_{other}(t) \quad (1)$$

where: $B_{animal}(t)$ represents the animal subsystem; $B_{human}(t)$ represents the human subsystem; $B_{other}(t)$represents all other components of the biosphere not explicitly distinguished within the operational domain structure.

This formulation preserves the ecological unity of the biosphere while allowing the identification of operational subsets relevant to One Health analysis. The distinction between animal and human subsystems therefore represents an analytical partition applied to the biotic stock, rather than a fundamental separation of system components.

In addition to abiotic and biotic stocks, the HEROS framework defines the heritage structural stock, $H(t)$. This stock represents the accumulated material and energetic structure of immovable cultural heritage. Heritage structural stock consists of persistent physical structures embedded within the abiotic environment and interacting with both abiotic and biotic components. It represents an accumulation of material and energetic resources resulting from past system processes and resource investments. The possibility to identify such stocks and flows is already proved in the literature [21].

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The HEROS framework further distinguishes, within the information stocks, the intangible heritage information stock, $I(t)$. This stock represents the informational component associated with heritage structures, including knowledge systems, cultural practices, symbolic meanings, and behavioural regulatory structures. This stock is formally defined as an information stock embedded within the system. Unlike material stocks, the information stock does not constitute a physical mass or energy reservoir, but functions as a regulatory structure capable of modulating system flows and influencing system stability.

For operational purposes, the HEROS framework also defines the human subsystem as a functionally distinguished component of the biotic stock, represented as $S(t) \subseteq B(t)$. This subsystem captures the specific interaction between human populations and heritage structures, while remaining formally embedded within the biotic stock. These stock definitions are generic system variables whose explicit physical interpretation and measurement must be defined in the context of specific applications.

2.4.3. Possibility of a Unified Metrological Basis

The HEROS framework adopts a bio-physical metrological approach grounded in thermodynamics. Within this approach, system variables, that refer to the amounts of resources available and flowing within the systems, can be quantified using energy proxies, that can be experimentally determined, representing the energetic resources required to generate, maintain, and regulate system structure and dynamics. The coherency, formal consistency and multidomain applicability of this approach is already proved in system ecology [17].

Social-ecological systems are open dissipative systems maintained in thermodynamic disequilibrium through continuous exchanges of energy and matter with their environment. The persistence of system structure depends on the continuous input of available energy extracted from environmental reservoirs and converted into structural, biological, and informational organization. The energy state of such systems, which can be expressed using Gibbs free energy, and its dynamics governs the system stability and evolution [22,23]. In particular, the availability extracted from environmental reservoirs constitutes the fundamental driver of system metabolism, supporting both biological processes and the maintenance of social and technological structures [24]. Thus, availability is an optimal candidate as universal energy proxy for quantifying system stocks and flows. The availability associated with a system stock, X, is defined generically as $\mathcal{A}_X$. Similarly, availability flows between the generic system stocks i and j are defined generically as $\mathcal{F}_{ij}$. These variables represent generic availability-based proxy quantities expressing the energetic content and energetic exchanges within the system.

The operational conversion of measured physical variables into availability proxies depends on the nature of the system component. Material stocks can be converted into availability proxies based on their embedded energy content and thermodynamic state relative to environmental reference conditions. Biological stocks can be quantified through their metabolic energy requirements, which represent the availability required to maintain biological structure. Structural heritage stocks can be quantified through the energetic investment required for their construction, maintenance, and preservation. Informational stocks, including intangible heritage, can be quantified through the energetic investment required for their transmission, preservation, and operational function within the system. This availability-based quantification provides a universal metrological basis for integrating abiotic, biotic, structural, and informational system components within a unified physical framework. Because availability quantifies the effective energetic potential embodied in system components, it allows the direct comparison of heterogeneous system variables within a common measurement domain.

Maintaining a generalized approach to the representation of a system, its stability depends on the balance between availability inputs and outputs, including also dissipation. Dissipative processes continuously degrade system organization, requiring continuous availability inputs to maintain

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system structure. The generic system equation describing the temporal evolution of availability embodied in system stocks t can therefore be expressed as:

$$\frac{d\mathcal{A}_X}{dt} = \sum\mathcal{F}_{in,X} - \sum\mathcal{F}_{out,X} - \mathcal{D}_X \quad (3)$$

where: (i) $\mathcal{F}_{in,X}$ represents availability inflows; (ii) $\mathcal{F}_{out,X}$ represents availability outflows; (iii) $\mathcal{D}_X$represents availability dissipation.

Within this framework, the functional role of heritage can be quantified as its capacity to influence availability flows and reduce availability dissipation. Within the HEROS framework, thermodynamic dissipation is interpreted as the irreversible loss of availability, corresponding physically to the degradation of system organization and functional integrity. Availability represents the capacity of a system to maintain its structured state, sustain internal processes, and perform work against environmental constraints. In physical, biological, and ecological systems, the maintenance of organization requires continuous throughput of energy, matter, and information, while dissipation represents the unavoidable irreversible loss associated with these processes. Within this thermodynamic framework, health can be rigorously interpreted as the capacity of a system to maintain its organized state against dissipative processes. A system remains stable and viable when availability input compensates for or exceeds dissipative losses. Conversely, when dissipation exceeds availability input, the system undergoes progressive degradation, reflected in loss of functional capacity, reduced resilience, and increased vulnerability to perturbation. The limiting condition in which availability approaches zero corresponds to thermodynamic equilibrium, at which point the system loses its organized structure and ceases to function as an organized entity. In biological systems, this condition corresponds physically to death; in ecological and social-ecological systems, it corresponds to system collapse or loss of functional integrity.

Within this context, dissipation provides a physically grounded and universal measure of loss of system health, as it directly quantifies the rate at which organized structure is irreversibly degraded. Health can therefore be interpreted as inversely related to dissipation rate: systems with lower dissipation rates maintain their organization more efficiently and exhibit greater stability, persistence, and functional capacity. This interpretation is consistent with the thermodynamic description of living and organized systems as open systems operating far from equilibrium. Such systems maintain their structure through a dynamic balance between availability inputs and dissipative losses.

Heritage structures and intangible heritage information stocks can regulate system interactions, modify system behaviour, and reduce the availability investment required to maintain system organization. This effect can be expressed generically as the difference in availability dissipation (i.e.,: loss of free energy, that can be converted into work) between the case in which a heritage asset is available, $\mathcal{D}_{heritage}$, with respect to the baseline scenario, without the heritage asset, $\mathcal{D}_{baseline}$:

$$\Delta\mathcal{D} = \mathcal{D}_{baseline} - \mathcal{D}_{heritage} \quad (3)$$

This quantity represents the availability 'savings associated with heritage presence. This approach is consistent with that adopted for the non-monetary representation of indirect ecosystem services associated to health and health losses [25]. Moreover, this representation is coherent with the fact that, in living systems, degradation phenomena correspond to a loss of capacity to convert the availability into work (as written by the authors of a research, the capacity to degrade the free energy into work), increasing, instead, the dissipation of the system [26].

Availability flows and dissipation terms are functions of system stocks:

$$\begin{aligned}\mathcal{F}_{ij} &= f_{ij}(\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_H, \mathcal{A}_S, \mathcal{A}_I)\\ \mathcal{D}_X &= g_X(\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_H, \mathcal{A}_S, \mathcal{A}_I)\end{aligned} \quad (4)$$

Then, interaction processes are defined as functional dependencies of flows and dissipation terms on system stocks. Heritage structural and informational stocks influence system dynamics not by introducing independent availability flows, but by modifying the functions governing system flows and dissipation. This distinction is fundamental. A flow represents a physical transfer of

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availability, while an interaction represents a regulatory or causal relationship, depending on different combinations of flows, that modify the rate of availability transfer or dissipation (i.e.,: flows).

Operationally, interaction structures are quantified by identifying measurable proxy variables that influence the governing functions $f_{ij}$and $g_X$. These variables correspond to measurable physical properties associated with system components, including environmental stability, habitat availability, structural persistence, and informational transmission capacity. In other words, each interaction structure can be represented generically as:

$$f_{ij} = f_{ij}(I_{ij,1}, I_{ij,2}, \dots, I_{ij,n}) \quad (5)$$

where $I_{ij,k}$represent measurable indicators influencing the interaction between stocks.

This formulation ensures that interactions are represented consistently with system ecology formalism, where system structure determines flow behaviour rather than constituting flows themselves. The metrological quantification of interaction structures therefore consists in identifying measurable proxy variables that determine these functional dependencies and converting them into availability-based indicators using the availability proxy formalism described in the previous section.

2.4.3. Possibility of a Representation of the System Dynamics

To enable the dynamic representation of the system behaviour, the HEROS formalism requires the identification of a set of phenomenological parameters governing the functional dependencies that generate the system dynamics. These parameters are related to the families of quantitative indicators, that will be detailed in the results. These parameters do not represent intrinsic "first-principles constants", but operational coefficients that summarize the intensity of processes and the responsiveness of flows to the current system state. They are determined through a structured workflow based on [27]: (i) evidence-based parameter identification, (ii) calibration of initial conditions and baseline operating regime, and (iii) verification of model robustness through sensitivity analysis. In particular, for each flow, a functional form is specified to express how the flow depends on the relevant availability stocks and on the measurable proxy variables (indicators) that modulate the system structure. Then, coefficients are determined using literature-derived characteristic times (turnover times, residence times, or characteristic rates) associated with the underlying process. Operationally, this corresponds to estimating coefficients from stock magnitudes and characteristic time scales, so that each process intensity is consistent with the known temporal dynamics of the phenomenon represented. This approach enables the construction of a parameter set even when direct experimental fitting is not available, because turnover-time evidence provides a physically interpretable constraint on flow magnitudes and response times. This procedure is coherent with the current practice for producing a dynamic representation of any system being assessed in the scientific literature [27].

Calibration is performed by defining: (i) A reference "baseline" configuration representing the expected stationary or quasi-stationary regime of the system under non-perturbed conditions; (ii) A consistent set of initial values for the availability stocks. The baseline configuration is used to ensure that, in the absence of perturbations or external forcing, the model reproduces the intended operating regime (e.g., stable stocks, or regular bounded oscillations when appropriate). Initial conditions are derived from available evidence (measured values when available, otherwise plausible reference values constrained by the proxy conversion and by known stock magnitudes). Then, parameters are adjusted within evidence-based bounds to satisfy two calibration requirements: (i) Preservation of the baseline operating regime; (ii) Realistic time scales for the transient response following perturbations.

Given the intrinsic limits of validating complex dynamic models when comprehensive empirical time series are unavailable, HEROS adopts a robustness-oriented verification strategy based on sensitivity analysis [28,29]. The minimal objective is to test whether the system behaviour (i.e., the main dynamic patterns, trends, threshold effects, and relative scenario ordering) is stable under plausible uncertainty in the most influential inputs and parameters. The verification procedure

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consists of varying, one at a time or in targeted sets, the most relevant parameters and/or initial stocks by a fixed percentage and re-simulating the system trajectories. Model robustness is supported when parameter perturbations produce quantitative shifts in trajectories but preserve the main qualitative patterns and comparative conclusions across scenarios. In other words, the model is considered verified for its intended purpose if the explanatory and comparative structure of outcomes remains stable under substantial parameter uncertainty.

## 3. Results

### *3.1. General System Structure*

Although The HEROS framework adopts a mathematical formalization derived from system ecology and thermodynamics of open systems, in which the system is represented as a set of interacting stocks connected by availability flows. This formalization provides a physically grounded representation of the system dynamics governing the interaction between abiotic, biotic, structural, and informational components.

The application of the framework described in the previous section results in the identification of immovable cultural heritage as a physically defined system stock embedded within the social-ecological system. This stock represents accumulated availability embodied in persistent structural configurations and informational systems. Within the resulting system structure, five primary subsystem components and related stocks should be formally identified ($\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_H, \mathcal{A}_S, \mathcal{A}_I$), representing the availability embodied in the abiotic environmental domain ($\mathcal{A}_A$), the biosphere ($\mathcal{A}_B$), the heritage structural stock ($\mathcal{A}_H$), the human subsystem ($\mathcal{A}_S$), and the intangible heritage informational stock ($\mathcal{A}_I$), respectively. These stocks emerge directly from thermodynamic constraints governing open dissipative systems. Any persistent structural or informational configuration requires continuous availability investment to counteract dissipative processes. Therefore, immovable cultural heritage emerges as a physically defined availability stock, whose persistence reflects accumulated energetic investment and whose presence influences system dynamics. The biotic stock, $\mathcal{A}_B$, represents the thermodynamic unity of the biosphere, while the human subsystem and animal subsystem represent operational subsets introduced for applicability within the One Health framework. This structure ensures compatibility with thermodynamic formalism while preserving the operational distinction required by One Health analysis. This result demonstrates that immovable cultural heritage can be formally represented as an intrinsic component of the system state, rather than as an external or purely symbolic element.

The mathematical formalization of the HEROS framework demonstrates that heritage structural and informational stocks influence system dynamics through regulatory interaction structures. These interaction structures do not correspond to independent availability flows, but to functional dependencies governing the magnitude and efficiency of availability flows and dissipation processes.

The evolution of each system stock is governed by the generic balance equation defined in the methods, where flows and dissipation terms are functions of system state variables. Within this formulation, heritage structural and informational stocks influence system dynamics by modifying the governing functions $f_{ij}$and $g_X$. This establishes heritage as a regulatory component capable of influencing availability transfer efficiency and dissipation rates throughout the system. This result demonstrates that heritage contributes to system dynamics through regulatory interaction structures, consistent with system ecology formalism.

### *3.2. Heritage Contribution to the Stability of the System Under a One Health Perspective*

The availability-based formalism enables the explicit identification of heritage contribution to subsystem stability through its influence on dissipation phenomena, that are generically used to represent the loss of health. The stability of a subsystem is determined by the dissipation rate associated with each stock:

$$\mathcal{D}_X = g_X(\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_H, \mathcal{A}_S, \mathcal{A}_I) \quad (5)$$

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The effect of the presence of heritage structural and informational stocks results in a change in each subsystem-specific dissipation rates:

$$\mathcal{D}_X^{heritage} < \mathcal{D}_X^{baseline} \tag{6}$$

Thus, the heritage contribution to subsystem stability can be expressed generically as:

$$\Delta\mathcal{D}_X = \mathcal{D}_X^{baseline} - \mathcal{D}_X^{heritage} \tag{7}$$

This quantity represents the reduction in availability dissipation associated with heritage presence. This result establishes a thermodynamically grounded metric for evaluating heritage contribution to system stability.

Entering into further detail, the HEROS framework enables the explicit identification of heritage contribution to the three operational domains of the One Health system: environmental stability, animal subsystem stability, and human subsystem stability. Within the availability-based formulation, heritage structural and informational stocks influence the dissipation rates associated with each of these domains. In particular, for the environmental domain, the influence is represented by:

$$\Delta\mathcal{D}_A = \mathcal{D}_A^{baseline} - \mathcal{D}_A^{heritage} \tag{8}$$

For the animal subsystem:

$$\Delta\mathcal{D}_{animal} = \mathcal{D}_{animal}^{baseline} - \mathcal{D}_{animal}^{heritage} \tag{9}$$

Finally, for the human subsystem:

$$\Delta\mathcal{D}_{human} = \mathcal{D}_{human}^{baseline} - \mathcal{D}_{human}^{heritage} \tag{10}$$

These quantities represent the reduction in availability investment required to maintain the stability of each subsystem due to the presence of heritage. Consequently, the total heritage contribution to One Health system stability is expressed in its generic form as:

$$\Delta\mathcal{D}_{OneHealth} = \Delta\mathcal{D}_A + \Delta\mathcal{D}_{animal} + \Delta\mathcal{D}_{human} \tag{11}$$

This formulation provides a physically grounded and operational definition of heritage contribution to the One Health system. It demonstrates that heritage contributes to One Health by reducing the availability investment required to maintain environmental stability, biological subsystem stability, and human system stability.

### *3.3. Formal Definition of Heritage Cost, Benefit, and Net System Contribution*

The proposed framework enables the definition of heritage maintenance cost as availability investment:

$$\mathcal{C}_H = \int \mathcal{F}_{maint,H}\, dt \tag{12}$$

In particular, $\mathcal{C}_H$ represents the availability required to preserve heritage structure and informational continuity. The heritage benefit, $\mathcal{B}_H$, is expressed as cumulative availability dissipation reduction:

$$\mathcal{B}_H = \int \Delta\mathcal{D}_{OneHealth}\, dt \tag{13}$$

Consequently, the net heritage contribution to system stability is defined as:

$$\mathcal{N}_H = \mathcal{B}_H - \mathcal{C}_H \tag{13}$$

This formulation provides a grounded criterion for evaluating heritage contribution to system stability.

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### *3.4. HEROS Framework Indicators*

#### 3.4.1. General Environmental Indicators

Following the parameterization strategy defined in the Methods section, in which availability flows and dissipation functions are formulated as functions of availability stocks and measurable proxy variables, the operational structure of the HEROS framework yields a specific and physically grounded set of indicator families. These indicators emerge as the measurable variables that parameterize the interaction structures governing availability transfer and dissipation across the environmental, biological, human, heritage, and informational domains. Their identification represents a direct outcome of the formal stock–flow representation and of the availability-based proxy conversion, as they constitute the observable quantities through which the functional dependencies of system dynamics can be quantified, calibrated, and evaluated. Accordingly, the HEROS framework defines a structured indicator system organized by domain, corresponding to the environmental, animal, human, structural heritage, and informational heritage subsystems.

The integration of system ecology formalism, availability-based metrology, and stock–flow mathematical representation results in the emergence of the HEROS framework as a physically grounded model of immovable cultural heritage within the One Health system. Within this framework, heritage structural and informational stocks act as regulatory system components that influence availability flow dynamics and reduce availability dissipation across environmental, animal, and human subsystems. This establishes immovable cultural heritage as an active component of the One Health system, contributing to system stability through thermodynamically defined mechanisms.

Importantly, these pathways are operationalized through indicator families that reflect widely adopted One Health and planetary health monitoring logics, where environmental drivers such as land-use change, habitat loss, biodiversity decline, climate stressors, and pollution are treated as upstream determinants of animal and human health outcomes [30]. Accordingly, the HEROS environmental domain adopts five complementary categories of indicators, selected to represent (i) environmental pressures and configuration, (ii) ecosystem integrity and connectivity, and (iii) proximate environmental conditions relevant to health risk and resilience, while remaining compatible with availability-based quantification through energetic/exergetic proxies.

Land-use continuity and landscape configuration indicators quantify whether the heritage site acts as an anchor of long-term land-use persistence and reduced disruptive transformation. Typical variables include land-use/land-cover change rates, fragmentation metrics, edge density, buffer-zone stability, and the persistence of traditionally managed land mosaics. These indicators align with One Health framings that explicitly identify land-use change and habitat loss as primary environmental drivers of health risks and instability.

Surface stability, erosion control, and hydro-geomorphological regulation indicators capture whether heritage-associated land management stabilizes soils and slopes and mitigates degradation processes. Variables include erosion susceptibility proxies, slope/soil exposure metrics, runoff regulation proxies, and disturbance frequency (e.g., landslides, gullying, local flooding). Such indicators are consistent with One Health governance and sustainability frameworks that treat environmental degradation and loss of regulating ecosystem services as upstream health determinants.

Ecosystem integrity and biodiversity–connectivity indicators represent the ecological interface structure around heritage (habitat quality, ecological connectivity, and biodiversity proxies) and are directly relevant to One Health logics linking ecosystem integrity to animal and human health [31]. Variables include habitat quality indices, species richness or functional diversity proxies (where available), connectivity measures (corridor presence, least-cost connectivity, patch cohesion), and indicators of ecological refuge function in anthropogenic landscapes.

Microenvironmental and exposure-relevant condition indicators are used to describing microclimatic stability and local exposure conditions relevant to wellbeing and ecological persistence. Variables can include temperature/humidity buffering metrics, shading/solar exposure proxies, wind

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sheltering, and vegetation–built interactions affecting microhabitat persistence. This category supports the interpretation of heritage as a structural modulator of environmental variability, which in HEROS maps to reduced availability dissipation in the environmental domain.

Environmental quality and contamination-pressure indicators are used to remain aligned with One Health practice, where pollution and environmental contamination are explicit determinant [32]. Consequently, HEROS includes indicators of air, water, and soil quality pressures at the site and buffer scale (e.g., particulate exposure proxies, water quality proxies, soil contamination screening variables, and pressure inventories). These variables connect heritage–environment interaction to the One Health environmental domain through measurable exposure pathways.

Taken together, these indicator families allow the HEROS framework to operationalize environmental-domain pathways as measurable determinants that can be translated into availability-based proxies (through the metrological approach defined in Section 2), supporting the quantification of heritage-mediated reductions in environmental dissipation $\Delta\mathcal{D}_A$ and their contribution to the integrated One Health stability term $\Delta\mathcal{D}_{OneHealth}$.

3.4.2. General Animal Domain Indicators

Within HEROS, animal-domain interactions are quantified as interaction structures that regulate the functions governing (i) availability dissipation associated with animal population persistence and (ii) availability investments required to maintain biological stability. In this operational sense, heritage affects the animal subsystem either when it modifies the determinants of survival, reproduction, movement, and stress, or when it modifies interface conditions that influence disease emergence, transmission, and surveillance detectability. This framing is consistent with One Health surveillance and wildlife health perspectives, that emphasize integrated monitoring of hazards and risks across species and ecosystems [33]. To make these pathways measurable and reproducible, the HEROS animal domain is operationalized through indicator families widely used (or directly compatible) with One Health animal-health and wildlife-health monitoring logics, including early warning and surveillance-oriented approaches.

Habitat/refugia function and resource-support indicators are related to the evaluation of immovable heritage as shelter or niche. These indicators quantify whether the heritage site provides stable microhabitats and resources that support wildlife persistence. Variables include availability of roosting/nesting structures, refuge density, microclimate buffering relevant to target taxa (e.g., thermal stability for roosts), and proxies of carrying capacity at site and buffer scale. This category supports the interpretation of heritage as a stabilizer that can reduce stress-driven dissipation in animal subsystems.

Population stability and biodiversity-relevant indicators quantify whether heritage-associated habitats support stable populations or assemblages. Variables include presence/absence of key taxa (including indicator species), population trend proxies where available, species richness or functional diversity proxies, and occupancy metrics. This family is consistent with One Health framings that explicitly include wildlife health and ecosystem-linked determinants.

Health-status and morbidity/mortality indicators describe the health condition of animal populations interacting with the heritage site, including morbidity/mortality signals, reproductive success proxies, and (where relevant) clinical/diagnostic indicators used in animal health surveillance. This category aligns with international animal-health surveillance logic, which emphasizes detection of presence/distribution of infection and early detection of emerging disease.

Wildlife–livestock–human interface and spillover risk indicators quantify conditions that modulate zoonotic risk at interfaces (contact rates, co-presence in space/time, attractiveness of the site to multiple host groups, proximity to livestock holdings, intensity of human visitation, and interface-specific exposure proxies). This category is consistent with One Health surveillance and prevention approaches that stress the importance of interface conditions and integrated surveillance across sectors.

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Stress, disturbance, and welfare proxy indicators capture whether the heritage site reduces or increases stressors that affect animal health and energetic expenditure (e.g., chronic disturbance due to tourism/traffic, noise/light pollution proxies, refuge accessibility, disturbance frequency). This family is important because stress and disturbance can be conceptualized as increased availability dissipation required for persistence, which is central to HEROS.

Surveillance feasibility and early-warning sensitivity indicators consider a heritage site as a monitoring node. Because One Health emphasizes early warning and integrated surveillance, HEROS includes indicators that describe whether the heritage site can function as a strategic observation point for wildlife health signals (e.g., feasibility of non-invasive sampling, sentinel potential, detectability conditions). This aligns with One Health surveillance guidance highlighting integrated systems, early detection, and intelligence.

#### 3.4.3. General Human Domain Indicators

Immovable cultural heritage influences human populations through both structural and informational mechanisms. As persistent physical structures embedded within lived environments, heritage sites contribute to shaping environmental exposure conditions, spatial organization, and patterns of human interaction with the environment. Heritage environments frequently exhibit structural characteristics that influence microclimatic conditions, environmental buffering, and spatial continuity, thereby affecting human environmental exposure. Environmental stability and reduced environmental variability have been associated with improved physiological regulation and reduced environmental stress burden.

Beyond their structural role, immovable cultural heritage sites embody and transmit intangible cultural heritage, including knowledge systems, symbolic meanings, practices, and historically accumulated environmental adaptations. These informational components influence human cognition, perception, and behaviour, supporting environmental orientation, cultural continuity, and behavioural stability. Persistent heritage environments function as spatial anchors for information storage and transmission, supporting long-term continuity of culturally embedded knowledge systems. This informational continuity contributes to cognitive stability by reducing uncertainty and the energetic and cognitive cost associated with environmental interpretation and decision-making.

Environmental psychology and public health research have demonstrated that interaction with culturally meaningful environments is associated with improved psychological wellbeing, reduced stress indicators, and improved cognitive function. These effects are consistent with One Health perspectives, which recognize environmental and cultural determinants as fundamental contributors to human health outcomes. Stable environmental and cultural contexts support physiological regulation and reduce chronic stress, which is a key determinant of long-term health.

Based on these mechanisms, the HEROS framework identifies several families of indicators relevant to the human domain, consistent with One Health, environmental health, and public health monitoring approaches.

A first category consists of environmental exposure and environmental quality indicators, which quantify the environmental conditions experienced by human populations interacting with heritage sites. These include indicators of microenvironmental stability, air and environmental quality proxies, thermal stability, environmental buffering, and indicators of environmental degradation or stability [34]. These variables reflect the environmental exposure conditions relevant to human health.

A second category consists of physiological and health status indicators, which describe human health outcomes associated with environmental conditions. These include indicators of stress-related health burden, physiological stress proxies, health outcome indicators used in environmental health surveillance, and proxies related to environmental health risks. One Health frameworks emphasize the importance of environmental determinants in shaping human health outcomes, particularly through exposure and environmental stability pathways [35].

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A third category consists of psychological and cognitive stability indicators, which describe the influence of heritage environments on cognitive function, stress regulation, and psychological wellbeing. These include indicators of psychological stability, stress reduction proxies, and measures of environmental perception and cognitive engagement [36]. Cultural heritage has been recognized as contributing to psychological wellbeing by providing stable environmental reference points and reinforcing cognitive continuity.

A fourth category consists of cultural continuity and informational transmission indicators, which capture the role of heritage as an information-bearing structure supporting the transmission and persistence of knowledge systems. These include indicators of cultural continuity, persistence of culturally embedded practices, continuity of site use, and indicators of knowledge transmission associated with heritage environments. These indicators reflect the informational dimension of heritage and its contribution to long-term system stability.

A fifth category consists of human–environment interaction and accessibility indicators, which describe the spatial and functional interaction between human populations and heritage sites. These include indicators of accessibility, continuity of human presence, patterns of use, and the stability of human–environment relationships associated with heritage environments. These indicators reflect the degree to which heritage environments remain integrated within human ecological systems.

Taken together, these indicator families enable the HEROS framework to capture the contribution of immovable cultural heritage to human subsystem stability within the One Health system. These indicators are consistent with One Health approaches recognizing environmental and cultural determinants as critical components of human health and wellbeing and support the interpretation of heritage as an active structural and informational component influencing human system stability.

#### 3.4.3. General Link Between the Indicator Families and the Dynamic Model

This subsection formalizes the general linkage between the HEROS indicator system and the dynamic stock–flow structure of the model, demonstrating how each indicator family might function as a measurable control variable governing availability transfer efficiencies, subsystem turnover rates, and dissipation modulation parameters. Each indicator family operationalizes measurable proxy variables that parameterize availability transfer efficiencies, turnover times, and dissipation rates within the HEROS stock–flow system. Indicators do not constitute independent state variables, but function as control parameters influencing dissipation modulation factors (e.g., $D_H^A, D_H^B, D_H^S$), inter-domain transfer coefficients, and subsystem turnover times. Through this linkage, the HEROS indicator system enables quantitative assessment of heritage-mediated reductions in environmental, animal, and human availability dissipation and their contribution to the integrated One Health stability term $\Delta D_{OneHealth}$. Table 1 provides a structured mapping between empirical observables and the implicit parameters of mathematical system representation.

**Table 1.** Examples of HEROS indicator families: their system sub-domains, functional role, scientific question implicitly addressed and potentially related type of parameters within the mathematical representation of the system.

| Subsystem domain | Example of indicator Family | Functional purpose | Scientific question | Potentially related type of model parameter |
|---|---|---|---|---|
| Environmental | Land-use continuity & landscape configuration | Detects whether heritage stabilizes spatial configuration and reduces disruptive transformation | How does heritage influence land use? | Dissipation rate coefficient $k_A$ |

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|---|---|---|---|---|
| | Surface stability & hydro-geomorphological regulation | Quantifies erosion buffering and soil stabilization | Does heritage reduce the degradation of soils? | Dissipation rate coefficient $k_A$ |
| | Ecosystem integrity & biodiversity–connectivity | Measures ecological interface stability and habitat continuity | Does heritage support ecological persistence and biodiversity? | Inter-domain transfer coefficient $k_{AB}$(environment → animal) |
| | Climate & micrometeorological regulation | Captures heritage-mediated modulation of climatic exposure and micro-meteorological stability | Does heritage reduce climate-driven environmental and biological stress? | Dissipation rate coefficient $k_A$ |
| | Environmental quality & contamination pressure | Captures pollution exposure pathways | Does heritage mediate exposure conditions? | Dissipation rate coefficient $k_A$ |
| Animal | Habitat/refugia function | Evaluates heritage as ecological shelter or niche | Does heritage reduce stress-driven animal dissipation? | Dissipation rate coefficient $k_B$ |
| | Population stability & biodiversity | Quantifies animal persistence and ecological stability | Does heritage enhance biological persistence? | Turnover time of animal stock $\tau_B$ |
| | Wildlife–livestock–human interface risk | Quantifies spillover interface conditions | Does heritage modulate zoonotic interface risk? | Dissipation rate coefficient $k_B$ |
| | Stress & disturbance proxies | Measures energetic cost imposed by disturbance | Does heritage reduce energetic stress load? | Inter-domain transfer coefficients $k_{BS}, k_{SB}$ |
| | Surveillance feasibility & early warning | Evaluates monitoring node potential | Can heritage function as early-warning node? | Dissipation rate coefficient $k_B$ |
| Human | Environmental exposure & quality | Quantifies human exposure conditions mediated by heritage | Does heritage reduce environmentally-driven human dissipation? | Dissipation rate coefficient $k_S$ |
| | Physiological & health status | Captures biological stability in human populations | Does heritage influence physiological regulation? | Dissipation rate coefficient $k_S$ |
| | Psychological & cognitive stability | Measures cognitive load and stress regulation | Does heritage reduce cognitive dissipation? | Turnover time $\tau_S$ |
| | Cultural continuity & informational transmission | Captures informational persistence and system memory | Does heritage preserve informational availability? | Dissipation rate coefficient of informational stock $k_I$ |

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| | | | |
|---|---|---|---|
| Human–environment interaction & accessibility | Measures integration of heritage in human ecological system | Does heritage remain integrated within human dynamics? | Inter-domain transfer coefficient $k_{HS}$ |

Within the HEROS framework, the proposed non exhaustive examples of indicators do not constitute independent state variables and are not treated as additional stocks or flows. Instead, they are related to structural and functional parameters, that are related to the equation dynamic coefficients, that govern the different types of availability transfer or degradation processes. This distinction is essential to preserve consistency with system ecology and thermodynamically grounded stock–flow modelling. The dynamic structure of the HEROS model is expressed through generalized availability balance equations of the form described by the following equation, having the same structure of Equation (3):

$$\frac{d\mathcal{A}_i}{dt} = \sum_j \mathcal{F}_{ji} - \sum_k \mathcal{F}_{ik} - \mathcal{D}_i \tag{14}$$

where $\mathcal{A}_i$ represents the availability stock of subsystem $i$, $\mathcal{F}_{ji}$ and $\mathcal{F}_{ik}$ represent availability transfers between subsystems, and $\mathcal{D}_i$ represents the rate of availability dissipation associated with irreversible processes. Availability flows and dissipation terms are expressed as functions of both availability stocks and measurable proxy variables:

$$\mathcal{F}_{ij} = f_{ij}(\mathcal{A}, I), \mathcal{D}_i = g_i(\mathcal{A}, I) \tag{15}$$

where $I$ denotes the set of indicator families identified in the previous subsection.

In operational terms, each dynamic coefficient appearing in these functional relationships is defined as a baseline value modulated by dimensionless functions of normalized indicator values. For a generic parameter, $p$, the functional dependence may be expressed as:

$$p = p_0 \cdot \Phi(I_1, I_2, \dots, I_n) \tag{16}$$

where $p_0$ represents a reference value consistent with literature-derived characteristic times or baseline process intensities, and $\Phi(\cdot)$ is a dimensionless modulation function derived from the chosen indicators, whose values are determined experimentally.

Indicators therefore influence system dynamics by modifying three principal classes of parameters: (i) Dissipation rates, which determine the rate at which availability is irreversibly degraded; (ii) Turnover times, which represent characteristic temporal scales of subsystem adjustment; (iii) Inter-domain transfer coefficients, which determine the efficiency of availability exchange between subsystems.

For example, environmental indicators related to land-use stability, microclimatic buffering, or contamination pressure influence the environmental dissipation coefficient through modulation functions, that adjust the baseline dissipation rate. If $\mathcal{D}_A = k_A \mathcal{A}_A$, then:

$$k_A = k_{A,0} \cdot \Phi(I_{env}) \tag{17}$$

where $k_{A,0}$ is a baseline dissipation coefficient and $\Phi(I_{env})$ reflects the normalized effect of environmental indicators. In this formulation, improved environmental stability (e.g., reduced fragmentation, enhanced buffering capacity) corresponds to reduced effective dissipation rates.

Similarly, turnover times, $\tau_i$, derived from literature-based characteristic times, are modulated by indicator values:

$$\tau_i = \frac{\tau_{i,0}}{\Phi(I)} \tag{18}$$

which implies that subsystem response speed depends on measurable structural or exposure-related conditions.

Inter-domain coupling coefficients are treated analogously. If availability transfer between subsystems is represented as:

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$$\mathcal{F}_{ij} = k_{ij}\mathcal{A}_j \tag{19}$$

then:

$$k_{ij} = k_{ij,0} \cdot \Psi(I) \tag{20}$$

where $\Psi(I)$captures the influence of interface-related indicators, such as ecological connectivity or human–environment interaction intensity.

A specific and central case within the HEROS framework is the heritage-mediated dissipation modulation factor, $D_H$, which captures the stabilizing role of structural and informational heritage stocks. The effective dissipation term may be written as:

$$\mathcal{D}_{\text{eff}} = \mathcal{D}_0 \cdot D_H \tag{21}$$

where $D_H = 1 - \beta \cdot \Theta(I_H)$ and $I_H$ represents the set of heritage-related indicators. In this formulation, heritage contributes to system stability by reducing the rate of availability dissipation across environmental, animal, and human subsystems. When heritage exerts a stabilizing influence, $D_H < 1$; in the absence of such influence, $D_H = 1$. The generalized forms of connections between the indicators and the parameters are summarized in Table 2.

**Table 2.** generalized forms of connections between the indicators and the dynamic model parameters.

| Parameter type | Generic mathematical form | Biophysical role |
|---|---|---|
| Dissipation rate | $k_A = k_{A,0} \cdot \Phi(I_{env})$ | Rate of availability loss |
| Turnover time | $\tau_i = \frac{\tau_{i,0}}{\Phi(I)}$ | Characteristic time scale |
| Transfer coefficient | $k_{ij} = k_{ij,0} \cdot \Psi(I)$ | Inter-domain coupling intensity |
| Dissipation modulation (heritage) | $D_H = 1 - \beta\Theta(I_H)$ | Reduction of dissipation |

This formalization ensures that the linkage between empirical observables and dynamic system behaviour is neither arbitrary nor purely conceptual. Instead, indicator families are systematically translated into dynamic coefficients through physically interpretable modulation functions consistent with availability-based metrology and turnover-time reasoning. Parameters are therefore not independently imposed but are derived from baseline process intensities constrained by characteristic temporal scales and modulated by measurable structural and exposure-related conditions.

Through this approach, the HEROS framework establishes a coherent mathematical bridge between measurable indicator systems and the generalized stock–flow equations governing availability dynamics. This enables quantitative assessment of heritage-mediated reductions in subsystem dissipation and supports the interpretation of immovable cultural heritage as an active regulatory component within the integrated One Health system.

### *3.5. Formal Definition of the HEROS Framework as a One Health System Model*

The The HEROS framework can be formally defined as a coupled dynamic system composed of five interacting availability stocks, $(\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_S, \mathcal{A}_H, \mathcal{A}_I)$, representing, respectively, environmental availability, animal biological availability, human biological availability, structural heritage availability, and informational heritage availability. Each stock evolves according to a generalized availability balance equation governed by inter-domain transfers and irreversible dissipation processes.

The environmental, animal, and human subsystems correspond to the operational domains emphasized within the One Health perspective. Their dynamic evolution is mutually coupled through inter-domain transfer coefficients that represent ecological connectivity, zoonotic interface conditions, and human–environment interaction structures. In this sense, HEROS explicitly embeds

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the core One Health principle that environmental, animal, and human health are dynamically interdependent.

Within this coupled system, immovable cultural heritage is represented by two distinct but interacting stocks: structural heritage ($\mathcal{A}_H$) and informational heritage ($\mathcal{A}_I$). These stocks do not merely receive availability flows but function as regulatory components that modulate dissipation rates, turnover times, and inter-domain transfer efficiencies across the environmental, animal, and human subsystems.

Formally, the dynamic equations of the One Health core subsystem can be expressed in compact form as:

$$\frac{d\mathcal{A}}{dt} = \mathbf{K}(\mathbf{I})\mathcal{A} - \mathbf{D}(\mathbf{I}, \mathcal{A}_H, \mathcal{A}_I) \tag{22}$$

where $\mathcal{A} = (\mathcal{A}_A, \mathcal{A}_B, \mathcal{A}_S)^T$, $\mathbf{K}$ is the matrix of inter-domain transfer coefficients, and $\mathbf{D}$ is the vector of dissipation processes modulated by heritage-dependent factors. The regulatory role of heritage is captured through modulation of dissipation rates:

$$k_i^{eff} = k_i \cdot D_H(\mathcal{A}_H, \mathcal{A}_I) \tag{23}$$

where $D_H \leq 1$ represents the heritage-mediated reduction of dissipative intensity. Through this mechanism, heritage reduces the rate at which availability is irreversibly degraded in the environmental, animal, and human subsystems.

This formalization establishes immovable cultural heritage as an active regulatory component within the One Health system. Rather than acting as a passive cultural artifact, heritage functions as a structural and informational stabilizer that modifies the thermodynamic balance of availability input and dissipation across domains. In this framework, system health is interpreted as the capacity of the coupled environmental–animal–human system to maintain organized availability against irreversible loss. By reducing effective dissipation rates and modulating coupling efficiencies, heritage increases subsystem persistence and enhances integrated system stability.

Therefore, HEROS provides a physically grounded mathematical representation of immovable cultural heritage as a stabilizing element within the One Health system, linking environmental integrity, animal persistence, and human health through explicit thermodynamic and dynamic mechanisms.

## 4. Discussion

### *4.1. Physical and Ecological Plausibility of Heritage-Mediated Environmental Stabilization*

The HEROS framework formalizes immovable cultural heritage as a stock of organized resources (mass, energy, and information) capable of influencing the stability of multiple domains through the modulation of system dissipation functions. This formal result is not merely conceptual, but is consistent with established physical, thermodynamic, and ecological principles governing the interaction between persistent structures and their surrounding environment.

The preservation of immovable cultural heritage contributes to environmental resource conservation primarily through the retention of embodied energy and the avoidance of material-intensive reconstruction processes. From a life cycle perspective, buildings and archaeological structures represent long-term accumulations of resources investments embedded in construction materials, structural systems, and site transformation. Conversely, demolition entails the irreversible loss of this embodied availability and requires renewed extraction, transformation, and high-dissipation industrial processes for replacement.

Life Cycle Assessment (LCA) research consistently shows that embodied energy constitutes a substantial share of total life-cycle energy demand in buildings [37]. Comparative analyses demonstrate that adaptive reuse and conservation strategies generally lead to lower cumulative energy demand and greenhouse gas emissions than demolition-and-rebuild scenarios over equivalent service lifetimes [38]. At the sectoral level, the building and construction domain accounts for approximately 37% of global energy-related $CO_2$ emissions when operational and embodied

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components are combined, indicating that avoided reconstruction can generate non-negligible environmental benefits [39].

Within the HEROS framework, these empirical findings correspond to specific modifications of environmental-domain parameters. In formal terms, demolition followed by new construction increases environmental availability dissipation $D_A$by activating high-intensity material and energy throughput processes. In contrast, preservation maintains an existing stock of structured material availability $A_S$ (structural heritage stock), thereby reducing the need for additional availability extraction from the environmental stock $A_A$. With this respect, the literature already reports some case studies, computing the cumulative availability embedded in heritage structures [40]. This mechanism can be expressed as a reduction in the effective dissipation rate coefficient governing environmental availability, $k_A$. Moreover, preservation reduces the inter-domain transfer coefficient, limiting the flow of environmental availability into high-entropy construction cycles. The structural heritage stock $A_S$, already embodying accumulated availability from past investments, continues to provide functional services without requiring a continuous reinvestment of raw materials. The same logic applies to archaeological sites and persistent anthropogenic landscape structures. Their conservation prevents additional land reconfiguration, infrastructure replacement, and material turnover. In HEROS terms, this corresponds to a reduction in environmental turnover rates $\tau_A^{-1}$ associated with land transformation processes. By stabilizing land-use configuration and preventing repeated cycles of extraction and reconstruction, heritage preservation reduces environmental throughput and limits availability dissipation.

Persistent physical structures modify local thermodynamic boundary conditions by altering temperature gradients, radiative exchange, air flow patterns, moisture transport, and surface energy balances. From a thermodynamic perspective, built structures affect local entropy production by redistributing heat fluxes and modifying exposure conditions. The thermodynamic analysis of built heritage has been extensively discussed in the literature, considering the implications of spatial configurations and materials on energy flows and dissipation mechanisms [41].

Historic buildings and archaeological structures frequently exhibit high thermal inertia due to their mass distribution and material composition (e.g., stone, masonry, earth-based materials). Studies in building physics and heritage microclimatology have shown that traditional constructions exhibit significant buffering capacity against short-term temperature fluctuations [24,42,43]. Thermal inertia reduces diurnal temperature variability, moderates peak thermal loads, and stabilizes indoor and near-surface microclimatic conditions. These buffering effects are particularly evident in historic urban fabrics, where dense morphology and massive envelopes contribute to reduced thermal amplitude compared to lightweight contemporary constructions.

Microclimate research in historic urban contexts further supports this interpretation. Studies on historic urban canyons and compact morphologies have demonstrated that traditional built environments can mitigate extreme thermal fluctuations and reduce localized heat stress, depending on material properties and spatial configuration [44,45]. These findings are directly relevant to the HEROS framework. In fact, microclimate conditions in historic urban context were considered in relation to the health of the urban population, as claimed also by Vitruvius in his book *De Architectura* [46,47].

At the landscape scale, similar stabilizing mechanisms have been documented in cultural landscapes and long-managed environments. Historical land-use systems associated with heritage sites often maintain mosaic structures that enhance ecological connectivity and reduce abrupt land-cover transitions [48]. Landscape fragmentation and rapid land-use change are widely recognized as drivers of ecological instability and biodiversity decline [49]. Where heritage sites anchor long-term land-use persistence, they contribute to reduced structural disruption and lower ecological turnover intensity. In HEROS terms, this corresponds to modulation of the environmental dissipation rate, $k_A$, resulting in reduced irreversible loss of environmental availability.

From a system ecology perspective, structural organization represents accumulated energetic investment embodied in material configuration [17]. Such organization does not cease to exert

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influence after its initial construction. Rather, it continues to modulate energy flows and dissipation pathways over extended temporal scales. Persistent structures act as constraints on energy gradients, redistributing flows and altering the spatial pattern of entropy production. The presence of a high-mass, thermally stable structure within a landscape modifies the spatial distribution of energy fluxes, thereby influencing the stability of adjacent ecological processes.

The above findings support the empirical plausibility for the central HEROS proposition that immovable cultural heritage can reduce environmental availability dissipation. The reduction of thermal variability, mitigation of exposure extremes, stabilization of land-use configuration, and buffering of ecological interfaces are all experimentally and observationally documented phenomena. The proposed framework formalizes them within a unified availability-based framework, translating documented stabilization effects into reductions of the environmental dissipation term within the coupled One Health system.

### *4.2. Heritage Structures as Ecological Stabilizers of Animal Subsystems*

The proposed framework formalizes heritage contribution to animal subsystem stability through the reduction in availability dissipation represented by the term $\Delta\mathcal{D}_{animal}$. This formulation is not speculative, but is strongly supported by ecological evidence, demonstrating the role of persistent built structures as habitat stabilizers across multiple taxa and landscape contexts.

Immovable cultural heritage structures frequently function as ecological refugia, providing shelter, nesting sites, and protection from environmental stressors [50]. Archaeological ruins, historic buildings, bridges, stone walls, and other long-lasting anthropogenic structures create stable microhabitats characterized by reduced environmental variability, structural complexity, and buffered thermal conditions. Habitat structure is widely recognized in ecology as a key determinant of species persistence, reproductive success, and trophic stability [51]. Structural heterogeneity increases niche availability and reduces competitive and environmental stress, contributing to biodiversity maintenance.

Numerous ecological studies have documented the role of anthropogenic structures in supporting biodiversity, particularly in landscapes where natural habitat availability has been reduced by urbanization or agricultural intensification. Historic buildings are known to provide essential roosting and breeding habitats for bats and birds [52,53]. Stone ruins and archaeological walls host reptile and invertebrate communities that would otherwise lack suitable microhabitats in modified landscapes [54]. Traditional rural constructions and dry-stone walls have been shown to enhance local biodiversity by offering microclimatic buffering and structural complexity.

These structures often provide microclimatic buffering that reduces thermal amplitude and exposure to extreme conditions, which is critical for species sensitive to temperature variability. Thermal stability within roosting or nesting sites reduces metabolic stress and energy expenditure required for thermoregulation, directly influencing survival probabilities [55]. From an energetic perspective, stress exposure increases metabolic demand and accelerates resource depletion. By contrast, refuge conditions that reduce thermal and predation stress lower the energetic cost of persistence.

Within the HEROS framework, these documented ecological mechanisms correspond to a reduction in availability dissipation associated with biological persistence. Reduced environmental stress translates into lower energetic expenditure required to maintain biological organization, effectively reducing the dissipation coefficient governing animal subsystem stability. In formal terms, habitat buffering provided by heritage structures contributes to lowering the effective dissipation rate $k_{animal}$, thereby decreasing $\Delta\mathcal{D}_{animal}$.

In addition to direct habitat provision, heritage sites may function as ecological nodes enhancing connectivity across fragmented landscapes. Landscape ecology research has demonstrated that structural elements embedded within anthropogenic matrices can act as stepping stones, supporting dispersal and gene flow (Saura et al., 2014, *Landscape Ecology*). Increased connectivity reduces local

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extinction probability and enhances metapopulation stability, which in dynamic system terms corresponds to reduced turnover stress and improved persistence.

From the perspective of system ecology, habitat structure represents accumulated organizational energy that constrains and channels biological flows. Structural complexity reduces entropy production within biological subsystems by stabilizing interaction networks and lowering stochastic mortality pressures. Persistent built heritage, therefore, acts as a structural constraint that modifies the energetic landscape experienced by organisms. These evidences support the interpretation of immovable heritage structures as stabilizing components, formalizing well-documented habitat stabilization effects within a thermodynamically grounded availability framework, translating ecological persistence into reductions of $\Delta\mathcal{D}_{animal}$ within the integrated One Health system.

### *4.3. Heritage Informational Stock and Stabilization of Human Subsystem Dynamics*

The HEROS framework identifies intangible heritage as an informational availability stock capable of regulating human subsystem dynamics and reducing availability dissipation, represented by the term $\Delta\mathcal{D}_{human}$. This formulation is not metaphorical, but grounded in empirical research spanning environmental psychology, cognitive neuroscience, stress physiology and cultural cognition.

Persistent physical environments, such as heritage buildings, historical buildings or archaeological sites, being preserved because of their symbolic meaning for a given human community, function as externally anchored memory scaffolds both at individual and at community level. According to distributed cognition theory, cognitive processes are not confined to neural substrates but extend into structured environmental supports that reduce cognitive load and uncertainty [56,57]. Cultural heritage sites can provide temporally-stable and spatially anchored informational cues, that support orientation, meaning attribution, and behavioural predictability. By externalizing information into stable environmental forms, heritage reduces the energetic and cognitive cost associated with reconstructing environmental models and adaptive strategies.

From a neurobiological perspective, long-term memory is not a static archive, but a dynamic and metabolically demanding process. Memory consolidation depends on repeated reactivation and progressive reorganization of neural representations across hippocampal–neocortical networks [58,59]. Stable environmental reference points, acting as temporally stable external landmarks, increase the probability of contextual reactivation by providing recurrent spatial cues that engage distributed memory networks. Repeated encounters with persistent landmarks facilitate pattern completion processes within hippocampal–cortical circuits, lowering the activation threshold required for retrieval. Thus, the hippocampus plays a central role in spatial memory encoding and contextual association by integrating environmental landmarks into cognitive maps. However, long-term memory stabilization involves the dynamics of distributed engram ensembles (i.e.,: ensembles of memory physical substrates, in the form of neuron populations, that undergo activity-dependent plastic changes during learning and that are reactivated during memory recall) shaped by activity-dependent synaptic plasticity, competitive allocation mechanisms, and sustained neuron–astrocyte molecular interactions across multiple brain regions [60,61]. Systems consolidation involves recurrent reactivation of distributed cortical traces. Conversely, without reactivation, synaptic connections weaken and memory persistence declines.

Within the HEROS formalism, chronic stress represents a condition of increased availability dissipation in the human subsystem. Sustained exposure to environmental unpredictability activates neuromodulatory systems responsible for vigilance and adaptive responsiveness, particularly the locus coeruleus–noradrenaline (LC–NE) system. Noradrenergic signalling modulates neural gain, attention, and synaptic plasticity [62]. While moderate activation enhances learning and memory consolidation, persistent tonic activation under chronic stress contributes to allostatic load and elevated metabolic expenditure [63,64]. Prolonged activation of the hypothalamic–pituitary–adrenal axis increases cortisol levels and physiological wear. In the HEROS model, such sustained stress-

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mediated activation corresponds to an increase in the effective dissipation rate of human availability, $D_{human}$. Environments characterized by spatial continuity, symbolic coherence, and predictability reduce sustained LC–NE activation and baseline arousal demands [65]. Persistent heritage landmarks, by reinforcing familiarity and contextual stability, plausibly contribute to a reduction in tonic neuromodulatory load, corresponding to $\Delta D_{human} < 0$.

At the cellular level, long-term memory consolidation is metabolically constrained. Activity-dependent synaptic stabilization requires coordinated astrocyte–neuron metabolic coupling. Astrocyte-derived lactate has been demonstrated to be necessary for long-term memory formation and activity-dependent gene expression [66,67]. Therefore, memory persistence depends on the availability of metabolic resources sufficient to sustain synaptic maintenance and transcriptional stabilization. Chronic stress increases metabolic demand and competes with these consolidation processes. Conversely, environments that reduce baseline stress preserve energetic availability that can be allocated to synaptic stabilization. Microglia further contribute to memory persistence through experience-dependent synaptic remodelling and extracellular matrix regulation. Experimental evidence shows that microglial dynamics influence structural stabilization of engram networks through inflammatory and structural modulation pathways [68]. Thus, long-term memory thus emerges from coordinated neuronal, glial, and metabolic processes that remain sensitive to environmental stability and physiological stress load [69,70].

A parallel evidence of this mechanism comes from the studies in environmental psychology, consistently demonstrating that exposure to coherent and culturally meaningful environments is associated with improved psychological wellbeing, reduced stress markers, and enhanced cognitive performance [71,72]. Public health syntheses further indicate that engagement with cultural and heritage environments correlates with lower stress biomarkers and improved self-reported health outcomes [73]. These findings provide empirical support for the interpretation that culturally meaningful environmental contexts reduce sustained physiological stress activation.

Beyond individual neurophysiology, intangible heritage stabilizes behavioural dynamics through intergenerational transmission of environmental knowledge. Knowledge systems embedded in cultural landscapes encode adaptive strategies for spatial orientation, risk mitigation, and resource management [74]. Informational continuity reduces behavioural turnover rates, limiting the energetic costs associated with repeated adaptive reorganization. From a system ecology perspective, informational organization represents accumulated availability embodied in structured knowledge systems [75]. Information constrains state-space variability and reduces entropy production by guiding energy flows into structured pathways [76]. Within HEROS, intangible heritage functions as an informational constraint that lowers the effective dissipation coefficient governing human subsystem dynamics.

Finally, other aspects that connect the intangible dimension of heritage with the information cycle is the inter-generational transmission of practices and know-how, that are coherent with the protection of the environment, as well as with the protection of the health of the biosphere. In fact, heritage sites often show us the relationship between human societies and the environment in the past, looking to the environmental and landscape context of heritage sites, as well as to the intangible dimensions (i.e.,: the practices, products, etc.) and the techniques (as practical knowledge and practices) [77–79]. Historical practices, as intangible counterparts, are also relevant for such a purpose [80]. Finally, the study of heritage sites and historical buildings present the evidence of historical circular practices, like the recovery and reuse of materials [81,82].

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*4.4. Integration and Operationalization of Heritage Within the One Health Paradigm*

The integration of cultural heritage, starting from the immovable assets, within the One Health paradigm is not merely a theoretical refinement, but raises a substantive ethical and governance question. If planetary, animal and human health are interdependent, as consistently affirmed within One Health framework, and if persistent cultural structures measurably influence the stability of these domains, then the complete exclusion of cultural heritage from health-oriented governance and actions represents a conceptual gap. With this respect, the joint action of the Italian Ministry of Health and the Italian Ministry of Culture allowing the medical prescription of visits to heritage sites and museums represent a pioneering decision [83]. This emerging line derives from the experience of "museum prescriptions" and broader "arts on prescription" programs. In fact, several Countries have piloted physician-prescribed visits to museums, galleries, and cultural institutions as adjunct interventions aimed at improving psychological wellbeing and quality of life. For example, a clinical study conducted in collaboration with the Montreal Museum of Fine Arts reported measurable improvements in wellbeing indicators among patients who received physician-prescribed museum visits [84]. More broadly, systematic reviews of "Arts on Prescription" programs have shown consistent associations with reductions in anxiety, improvements in mood, enhanced social connectedness, and perceived health benefits [85]. While these interventions are primarily situated within psychosocial health frameworks rather than biomedical treatment paradigms, they demonstrate that cultural environments can be formally integrated into care pathways.

However, integrating heritage into One Health does not imply medicalizing cultural heritage or reducing it to a therapeutic instrument. Rather, this choice starts from recognizing that certain heritage environments historically emerged as infrastructures of wellbeing and that their stabilizing functions remain structurally relevant within contemporary socio-ecological systems. Historical evidence supports this interpretation. In ancient Mediterranean cultures, healing was often embedded within environmental and architectural design. The sanctuaries of Asclepius, such as those at Epidaurus, Kos, and Pergamon, were spatially organized complexes integrating landscape orientation, water management, acoustic design, ritual practice, and communal gathering spaces in ways that facilitated physiological and psychological restoration [86,87]. These were not hospitals in the modern sense, but carefully structured environments in which architecture, ecology, and symbolic coherence interacted to promote conditions conducive to recovery. Similarly, classical theatres combined spatial geometry, acoustic optimization, and collective experience in ways that regulated emotional and cognitive states at a community scale [88,89]. The integration of natural resources into healthcare sites was characteristic too. In fact, in Greco-Roman antiquity, natural sites such as mineral springs, sacred waters, and forested sanctuary landscapes were systematically integrated into therapeutic practices, functioning as environmental components of healing infrastructures rather than as purely symbolic settings [90,91]. Recent developments in the archaeology of medicine further demonstrated that integrated forms of human–animal–environmental care are not exclusively modern constructs but have deep historical precedents documented in material and archaeological records. Deep-time analyses reveal that past societies implemented relational and multispecies care practices embedded within specific landscapes and built environments, anticipating core principles of contemporary One Health thinking [92]. These examples illustrate that the relationship between built form, environmental configuration, and health has long been recognized as structurally embedded rather than incidental.

Contemporary One Health frameworks emphasize prevention, environmental stewardship, and cross-sectoral governance, particularly in relation to zoonotic risk, biodiversity loss, and ecosystem degradation [93]. However, in practice, One Health policies predominantly focus on infectious disease interfaces and environmental contamination, while largely overlooking the stabilizing structural and informational roles of cultural landscapes and built heritage.

The HEROS framework provides an operational mechanism to address this omission by formalizing heritage as a regulator of availability dissipation across environmental, animal, and human subsystems. The ethical dimension of this integration rests on intergenerational justice. If

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heritage embodies accumulated structural and informational availability capable of reducing system-wide dissipation, its preservation becomes not solely a matter of cultural memory but also of preventive ecological responsibility. Heritage conservation can therefore be interpreted as a preventive, system-level health intervention—not because it cures disease, but because it contributes to lowering entropy production across interconnected domains. Integrating heritage into One Health governance thus extends preventive health strategies beyond biomedical interventions to include structural and informational regulators already embedded within landscapes. This integration is neither symbolic nor economically reductionist. It is a physically grounded, ethically justified, and operationally feasible extension of the One Health paradigm.

## 5. Conclusions

This study has introduced the HEROS framework (HERitage One Health System), a physically grounded model that formalizes heritage, with a special focus on immovable heritage assets, as an active structural and informational component of the One Health system. By integrating system ecology, availability-based metrology, and stock–flow mathematical formalism, the framework demonstrates that cultural heritage is not merely a symbolic or economic asset, but a persistent resource stock capable of modulating dissipation dynamics across environmental, animal, and human subsystems.

The central result of the study is the formal identification of heritage-mediated reductions in subsystem dissipation as measurable contributions to integrated system stability. This allows heritage to be interpreted within a thermodynamic and ecological logic, where stability, resilience, and health are understood as emergent properties of regulated availability flows. Within this perspective, heritage acts as a long-term infrastructural investment that continues to influence system dynamics long after its initial construction.

From a research standpoint, the framework opens a new interdisciplinary domain at the interface between heritage science, system ecology, neuroscience, environmental health, and sustainability modelling. It provides a common physical language for integrating cultural heritage into quantitative environmental and health models, enabling scenario simulations, sensitivity analyses, and cross-domain comparison using non-monetary, physically interpretable metrics. This creates opportunities for empirical validation studies, longitudinal analyses of heritage landscapes, and integration with spatial data, remote sensing, and environmental monitoring systems.

From an economic perspective, the framework supports a shift from heritage as cost-centre to heritage as stability infrastructure. By conceptualizing preservation as a strategy that reduces long-term system dissipation, HEROS provides a physical rationale for adaptive reuse, conservation-based land management, and heritage-centred urban planning. Over the medium to long term, such an approach may inform cost-benefit analyses that incorporate reduced environmental volatility, enhanced ecosystem stability, and improved human subsystem regulation. This perspective encourages investment strategies that recognize heritage preservation as a contribution to long-term resource efficiency and systemic risk reduction.

From a societal perspective, the framework reinforces the role of cultural heritage as a stabilizing component of collective continuity. By formalizing the link between environmental structure, informational persistence, and human physiological regulation, the study highlights how heritage contributes to cognitive stability, behavioural coherence, and reduced stress-related dissipation within human populations. In the long term, this supports resilience not only at the ecological and environmental levels, but also at the level of cultural identity, intergenerational knowledge transmission, and social cohesion.

Importantly, although the present study focuses primarily on immovable cultural heritage, the formal structure of the HEROS framework is not limited to it. The same availability-based logic applies to natural heritage, including forests, wetlands, geological formations, rivers, sacred natural sites, and other long-standing ecological structures that function as persistent environmental stocks. Natural heritage likewise embodies accumulated mass, energy, and information, and similarly

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modulates dissipation dynamics across environmental, animal, and human subsystems. For this reason, within the HEROS framework the concept of heritage is treated inclusively, encompassing cultural and natural heritage, material and intangible components, whenever they act as persistent structural or informational regulators of system stability. The mechanism of action (modulation of dissipation rates, turnover times, and inter-domain transfer coefficients) remains formally identical. Moreover, the framework avoids the medicalization or instrumentalization of cultural heritage. Instead, it situates heritage within a broader logic of system organization, where structural and informational continuity contribute to stability across scales. This offers a new conceptual foundation for integrating heritage within sustainability and One Health strategies without reducing it to economic or therapeutic functions.

Ultimately, the conceptual separation between 'natural' and 'cultural' heritage appears increasingly artificial and should be overcome in favour of an integrated notion of heritage as a coupled structural–informational continuum. In parallel, the implicitly anthropocentric framing of One Health requires refinement, which could be more coherently articulated to include the abiotic subsystems, the biosphere and the noosphere. Within this perspective, both natural and cultural heritage would emerge as a regulatory interface across planetary (abiotic), biological, and cognitive domains, rather than as a residual category external to health governance.

In conclusion, the HEROS framework demonstrates that immovable cultural heritage can be rigorously modelled as a regulatory component of social–ecological systems. By reducing availability dissipation and stabilizing cross-domain interactions, heritage contributes to the persistence of environmental, biological, and human subsystems. This interpretation provides a new physical basis for heritage policy, sustainability governance, and integrated health-environment strategies, with significant implications for research, economic planning, and long-term societal resilience.

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