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Review

Ecoexergy in the context of environmental sciences

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Abstract: Nowadays, it is possible to assert that the causality of environmental problems entails a complex social, economic, cultural and political background; faced with such a situation, it is essential to have an operational science that considers the human factor that is in constant interaction with the environment (socio-ecological systems), while seeking sustainable development. Because of that, it became necessary to join different disciplines in a construct called Environmental Sciences, whose main objective is to study and solve problems related to human-environment interactions.

Endorsing the concept of exergy to an interdisciplinary science implies understanding how society satisfies its needs with the natural resources provided by the various ecosystems and how they sustain demand in the man-environment interaction cycle, starting from the development of structural and functional attributes in a dynamic flow of matter and energy. This can be addressed with the first and second laws of thermodynamics by allowing the use of holistic indicators in the Environmental Sciences; one such indicator is ecoexergy, which describes the state of an ecosystem based on the biomass content and genetic information. Thus, this work presents an outline of the incursion of exergy in the context of environmental sciences, which implies that the ecosystem is an open system whose behavior adheres to the laws of thermodynamics.

Keywords: ecoexergy; thermodynamics; ecosystems; interdiscipline; complexity

1. Introduction

Nowadays, it is recognized that ecosystems maintain and self-regulate through the fulfillment of their functions, with a tendency to conformations of low entropy (i.e., maximum amount of energy to perform useful work), and the consequent generation of stable states of equilibrium [1,2]. Similarly, the participation of human beings in the thermodynamic configuration of such ecosystems is undeniable, which consolidates the so-called socio-ecological systems [3], while environmental problems are recognized in a context that implies the imminent interaction of the social, economic, cultural and political spheres [4].

The previous conjecture accepts a change in the level of complications of environmental problems and offers new challenges that determine the intrinsic complexity of the problem and the possible solutions from the articulations and compromises between the different components [5]. Hence, the Environmental Sciences (Esc) are primordial in the search for new knowledge in order to understand the development of the environment (socio-ecological systems) with the consequent proposal of solutions to the problems that have arisen [6].

By incorporating thermodynamics along with Esc within the umbrella of an interdiscipline implies knowing the interactions between biophysical and social factors of socio-ecological systems at different scales of time or organization, given that this science contemplates the complexity between these relationships [1,7]. Similarly, it is recognized that the majority of physical processes in the universe can be addressed by thermodynamic.

As a starting point, ecosystem services, which is one of the ESc constructs, can be considered, given that there are variables that link ecosystems with the social circumstances, which enables an outline of how socio-ecological systems can be understood as thermodynamic systems: open systems with energy flows whose efficiency is reflected in the quality of the obtained services [3,8].

Along the same idea, efficiency in the use of such energy flows by the ecosystem can be addressed by ecoexergy [9], which, in general terms, describes the level of development or complexity of an ecosystem based on its components and configurations and how they will seek to maximize useful energy [10]. Thus, this review aims to outline the thermodynamics of ecosystems in ESc within the idea of the interdiscipline that they proclaim, which allows the use of holistic indicators, such as exergy, in order to understand the current state of a given ecosystem.

2. Environmental science

The interest in environmental problems has rapidly increased since the end of the 60’s, which has led to the generation of studies that recognize the existence of environmental interrelationships and how some changes in nature have occurred due to anthropogenic intervention [11]; eventually, the confluence of these studies would end up building the terminology and theories used by ESc [12].

It is essential to emphasize that ESc belongs to a context that is far from the prevailing scientific method in the different traditional disciplines, given that it has forged procedures in its studies that seek a real interaction as a result of the growing social awareness that recognizes the vulnerability of the environment to human intervention [13]. Therefore, ESc can be defined as an operational science whose object of study lies in the interactions between nature and society [14].

However, the consolidation of these procedures has involved epistemological reflections, particularly when building of new knowledge while promoting a change in the conception of disciplines at the same time; this places ESc in the field of interdiscipline, in a way so that understanding an environmental problem requires a common dialogue between different disciplines, encompassing both the physical-biological sciences and the social sciences [15].

To clarify, in the context of Esc, it is necessary to individually address different areas of knowledge in order to not only integrate, but to harmonize the contributions of each one of them to be able to either understand, manage or resolve environmental problems [15].

3. The ecosystem as a thermodynamic system

The structure and funciton of an ecosystem are compatible with the description of an open system whose dynamics allow external energy inflows to move away from thermodynamic equilibrium and continue in a low-entropy configuration, thus fulfilling the so-called thermodynamic direction of evolution, that is, to dissipate and degrade the energy that flows into the system, so that as an open system, the ecosystem increases its performance at the expense of exergy content [16].

The main source of energy for the vast majority of ecosystems is the visible light of the solar radiation spectrum, from which photosynthesis begins. Subsequently, through various biological processes, the energy will be used for the growth of the system, as well as the development of the organization such as increases in food webs with the consequent increase in biomass, which, in turn, will generate a growth in genetic information [17,18]. Thus, ecosystems degrade solar energy inputs in a self-sustaining environment through the development of organized structures [19]. It is noteworthy that, alluding again to photosynthesis, vegetation largely determines the presence of species at the different levels of the food chain for an ecosystem [20].

From the previous idea, it is to be understood that the cycle maintains the ecosystems. It begins with primary consumers (organisms that feed on plants) that assimilate around 10% of the primary production, which is the difference between the total production of organic matter and its rate of decomposition, while the remaining 90% dissipates in the form of heat. This is the general rule, so ascending in the food chain, predators will use only 10% of the production from primary consumers, and so on [21]. It is noted that respiration is the process by which organisms use energy in functions such as reproduction and maintenance, so that, cellular respiration it could be considered as the inverse of photosynthesis [22]. Organic waste will decompose and be reduced to become available primary inorganic compounds in these cyclic processes [21].

These processes define the potential amount of energy present in the ecosystem needed to perform work that is useful for maintenance. In thermodynamic terms, this behavior ensures that ecosystems are far from equilibrium, understanding equilibrium as the configuration in which the system can no longer perform any work given the absence of energy gradients [23].

4. Ecoexergy

The term "exergy" refers to the quality of energy, given that the energy used for any process will continuously lose quality, thus reducing its exergy. Fundamentally, exergy is both a quantitative and qualitative measure (in terms of ecosystem services) of the energy flow of a given system. At the same time, exergy measures the thermodynamic distance of a system from equilibrium using its surrounding environment as a reference [24].

Thus, in thermodynamics, exergy can be seen as ideal work and denotes a certain link with the production of entropy that involves the loss of exergy (equivalent to useful work not done). Therefore, contrary to exergy, increases in entropy describes the inability to do work in a system [25].

Similarly, exergy denotes the maximum capacity of energy to do useful work [26]. The term ecoexergy is generally used in the specific case of ecosystems, where it measures the possibility of the ecosystem to accept and use external energy flows for its own maintenance; it uses the same ecosystem as a reference state and considers biomass as an energy storage [21,27].

Therefore, based on the biochemical components and the chemical energy contained in the biomass, it is possible to perceive the work capacity of an ecosystem, or ecoexergy, which can be calculated using the following formula (Eq 1):

$$Ex = \sum_{i=1}^{N} C_i \cdot \beta_i \tag{1}$$

Where β is considered as a weighting factor related to the information stored in the genes of a certain organism [21]. Similarly, β denotes the probability of forming a specific organism according to the conditions established by the ecosystem. Therefore, this factor can be seen as the meeting point between information theory and thermodynamics, since it recognizes biodiversity as a driver of ecosystem functioning. This diversity is intrinsically related to the genetic diversity that gives organisms functional diversity, which ,in the field of complex systems, refers to the number of valuable ecological interactions [28]. Thus, the β values reflect the complexity of organisms [29].

C_i represents the concentration of the component i as the similarity of the movement of energy through the components of an ecosystem once it has been incorporated into organic matter [22]. Therefore, in such a mathematical expression, it is noticeable that exergy expresses the useful energy used in maintaining the ecosystem due to the free energy of the many organic compounds plus the information carried by living organisms [24].

However, it is mandatory to accentuate the specificity in the concepts of exergy and ecoexergy, given that the first addresses energy efficiently with attention to thermal and mechanical balance with the environment, which indicates the maximum available energy that can be transformed into useful work; however, it dismisses environmental implications. Despite this, recently, exergetic analyses have incorporated the approach of flows from ecological processes and the production of goods and services. Regarding ecoexergy, its definition can be considered an extension of the first, since it implies energy quality (useful work) with reference to environmental processes that, for the effect of ESc, incorporates interactions with the environment, hence the result of a good indicator in the evaluation of anthropogenic conditions on the availability of energy in ecosystems. Thus, despite the specificity of these concepts, their contribution to understanding the possible interactions between energy and the environment is highlighted. From the above, the following section highlights the behavior of the ecosystem around the thermodynamic implications and the possible place of the exergy approach in its study.

5. Exergy and ecosystems

As has been stated before, just as living systems, ecosystems can be considered open thermodynamic systems whose operation greately depends on biomass, which stands out as a storage of useful potential energy that is used in the different processes of maintenance for the ecosystem; in a complementary way, the energy that is not used in such processes dissipates to the environment as heat [30], which is considered a form of final state in the process of energy degradation within ecosystems, so that heat can be seen as a form of high entropy [7].

Likewise, both growth (related to how big or small the system is) and development (levels of organization) of an ecosystem are processes that continually keep it far from either equilibrium or the state in which the system cannot do any work since there is no ecoexergy or exchange gradients [19,31]. It should be noted that such processes are irreversible, so the function of ecosystems will be described by the first and second laws of thermodynamics. Energy flows constantly towards the development of organisms whose eventual death and consequent self-decomposition ensures their reincorporation in new energy-generating processes within the ecosystem [7].

Continuing with the laws of thermodynamics, it is necessary to notice that there is a tendency to maintain a state of low entropy with respect to the environment, which can be achieved from various biological processes after the initial capture of energy (visible light of the solar radiation spectrum) [32]. Subsequently, the flow of energy in metabolism urges the creation of lower quality forms of energy (compounds that contain chemical energy), with the consequent dissipation of energy (heat) [33].

It is important to remark the urgency for processes that increase the amount of biomass, which are considered structural growth, since they are related to the increase of components within the ecosystem [34]. At the same time, these components create connections that promote the growth of the entire system since there will be greater flows of matter and energy. Likewise, such growth will be accompanied by a rise in the information that gives the ecosystem a genetic complexity in an environment of energy efficiency. All in all, the process is consolidated in the maximization of exergy within the ecosystem, which will flow through it as useful energy for its self-maintenance [29,35].

Because of that, a distinction is made between energy and material efficiency, which is related to the quality of ecosystem services, since exergy can also be used in the analysis of energy resource flows; from the second law of energy, it is possible to evaluate the quality of energy (exergy) in relation to the transformations of energy-carrying resources [36]. Thus, the exergy alluding to resources is defined by its physical and chemical components. Physical exergy is concerned with physical processes that involve only thermal interactions with the environment, while chemical exergy refers to the maximum amount of work that is obtained when resources or materials are transformed from the ambient state to the dead state, with the consequent heat transfer and exchange of substances with the environment [37].

Therefore, the chemical exergy will be a function of the composition of the material, which, in turn, is characteristic of the environment [38]. Calculating chemical exergy can be complicated, although there are currently tables with such values obtained from the concept of standard chemical exergy (25 °C, 1 Atm), which also considers the standard concentration of the reference species in the environment. Likewise, only the change in concentration of the components of the material to be evaluated can be addressed, as shown in the following formula:

$$Ex_{ch} = nT_0R\sum_i y_i \, ln\frac{y_i}{y_{0i}} \tag{2}$$

where n is the number of moles of the material, y_i,y_{0i} is the mole fraction of the i-th component in the material and R is the universal gas constant [37].

Similarly, as established in the definition of ecoexergy, it considers the contribution of the components, including the energy associated with the organization (information), which, in turn, is related to the survival and growth of organisms in the ecosystem [39]. From this, the extension of Darwin's theory to ecosystems is noted; consequently, it is possible to establish the exergy in the construction of other organisms, that is, the cost of energy to build superior organisms in the dynamics of the ecosystem, from the construction of energy storage and flow models with the analysis for each of the components in the model, is given in the following equation:

$$Ex = R \cdot T \cdot \sum_{i=0}^{N}[c_i \cdot \ln\left(\frac{c_i}{c_i^{eq}}\right) + \left(c_i - c_i^{eq}\right)] \tag{3}$$

where R is the gas constant, T is absolute temperature, c_i corresponds to the concentration of component i in the ecosystem, 0 indicates the inorganic components of the element considered and c_i^{eq} is the concentration of component i in thermodynamic equilibrium [40].

6. Ecoexergy and the environmental sciences

In general, it is possible to affirm that environmental problems are the result of intrinsic social, economic, cultural and political relations; thus, there is an urgent need for an operational science that considers the well-being of humans without compromising sustainability. This implies the practice of new analytical and methodological forms in order to understand the interrelationship between importance of society and the environment in the configuration of global environmental change [36].

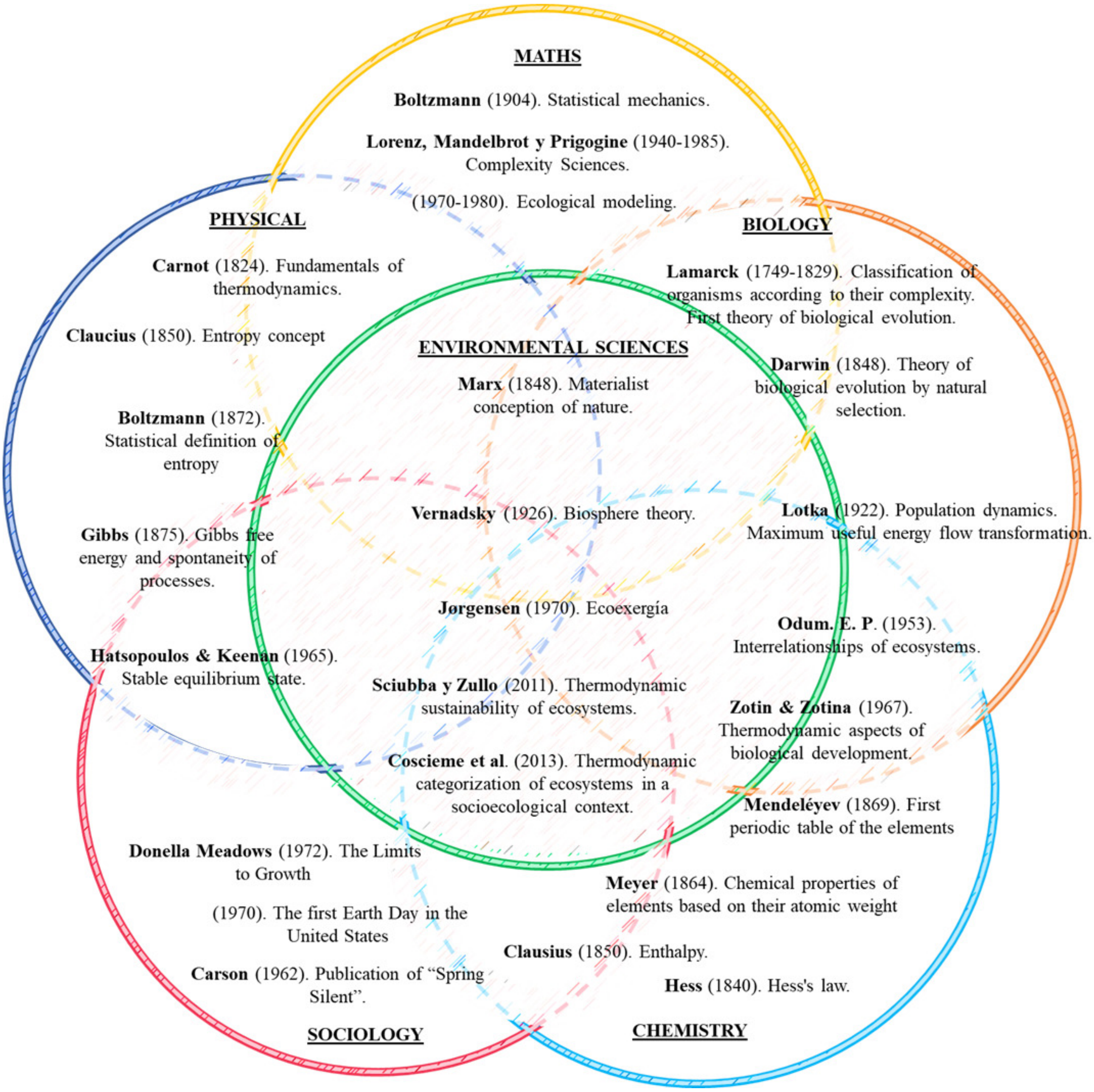

Figure 1. Historical deployment of knowledge and theories that led to the conjunction of thermodynamics and exergy in the context of environmental sciences. Five conjugated blocks are evoked in the center (environmental sciences). Physics encompasses the development of thermodynamics. Mathematics alludes to ecological modeling. Biology and chemistry emphasize the union of thermodynamics with both. Sociology with contributions in socio-environmental studies. The central block shows some of the

important events in the inclusion of ecoexergy in environmental sciences from an interdisciplinary perspective as a result of the development of other disciplines. Adapted from “Thermodynamics in Ecology—An Introductory Review,” by S. N. Nielsen et al. [7].

However, for this to happen, it is necessary to refer to the confluence of different disciplines; this is the case of EScs whose main objective is to study and solve problems related to the human-environment interaction, for which the prevailing scientific method is insufficient [12].

Endorsing the concept of ecoexergy in ESc theory (Figure 1) requires an understanding on how society satisfies its needs, thanks to natural resources extracted from various ecosystems, and how they sustain the human-environment relationship through the development of structural and functional attributes in a dynamic flow of matter and energy [41] that evokes the complexity of ecosystems; this will be described by the continuous integration of biodiversity with environmental factorsand the specialization of species, which includes feedback mechanisms as well as regulation and the degree of adaptation [42]. The first and second laws of thermodynamics are noted as essential foundations in the knowledge generation that helps to understand and quantify the environmental impacts [43,44]. Thus, it should be noted that society consumes and extracts natural capital from either ecosystems or ecosystem services, also called ecological functions of value to society, will depend on the energy effort necessary for its production [45].

If all life and activities are subject to these thermodynamic principles, it is easy to see that, when energy is converted from one form to another, there is no total energy loss within an ecosystem, though there is a loss of useful energy [46]. Thus, the "ecological law of thermodynamics" appears [47]; it uses the term ecoexergy to describe the useful energy that is harnessed by ecosystems during maintenance processes. Therefore, it prompts a thermodynamic optimization in nature [7].

Thus, the dissipation of energy from states of low entropy to those of high entropy generates structures with a high degree of complexity and organization, with the consequent accumulation of exergy through the development and evolution of living systems [48]. Because of that, the complexity of the object of study can be deduced in terms of the development of interrelationships with feedback, memory, adaptive capacity, and non-linear behaviors. Thus, this complexity of the systems belongs to different material domains (physical, biological, social, etc.); therefore, its study can only be approached under the protection of the theory of complex systems, which deals with the use of interdisciplinary approaches, with the purpose of reaching an adequate interpretation of the functioning of such a system as an organized whole[49].

Regarding ESc, it is essential to mention that the interdiscipline aspect lies at its core, which allows for the conjunction of historical efforts of different disciplines in order to understand the concept and calculation of ecoexergy, which was first applied during the late 1970s in ecological studies [7].

Although the earlier authors, such as Lotka, perceived that there is an imminent participation of energy within the dynamics of biological systems from the interaction of species [50], it was not until several years later that the idea of a thermodynamic optimization was articulated for ecosystems, population or organisms, in a way that they will perform according to the conditions imposed by the environment. After that conjecture, the confluence of knowledge that would promote the development of ecoexergy was visualized as an indicator of the state of an ecosystem or its strata [7], whose conclusion is a generalization of the Carnot cycle for biological systems (Figure 2), in which the obtained work can be approximated from exergy [51]. As mentioned, the activities carried out by an ecosystem, immersed in the socioecological systems, require energy that can perform work for the maintenance of the same ecosystem while providing services to the socioeconomic systems.

In this context, the capacity for work can be seen as the total amount of ecoexergy offered by an ecosystem [44].

Likewise, the development of ESc shows a glimpse of the panorama on the use of ecoexergy as an objective function in various studies, such as those of Sciubba and Zullo (2011), who explored the concept of thermodynamic sustainability of ecosystems based on the use of fossil resources, which revealed the self-preservation capacity of ecosystems based on their intrinsic complexity [52]. Wang et al. (2017) evaluated the ecosystem health of Lake Taihu, China from a thermodynamic perspective through specific ecoexergy; their results recommend the use of both indicators for the early detection of alert statistical parameters such as variance, rate of return and asymmetry to predict changes in the state of the lake [23]. Lastly, Zhang et al. (2019) evaluated the impact that subsidence in coal mines has on wetlands, through the use of ecoexergy and structural ecoexergy [24]. Both indicators facilitated the analysis of various changes in the ecosystem and their effects by making the quantification of ecoexergy values of the ecosystem components possible, thereby defining the factors that lead to changes in it. Buonocore et al. (2020) used ecoexergy in the evaluation of the biophysical value of the ecosystem in Punta Campanella, Italy with an interdisciplinary approach; they found a high value of ecoexergy for the Posidonia ecosystem, which was due to the high density of biomass as a reflection of the input flows used for the generation of a high biodiversity [9]. Meanwhile, Marchi et al. (2012) studied the health of an aquatic ecosystem through thermodynamic indicators to understand the effects of eutrophication and perturbations caused by alien species [53]. They concluded that ecoexergy is a good indicator of efficiency by transforming direct and indirect solar energy inputs in the organization, regulation and maintenance, which eventually affects the quality of ecosystem services.

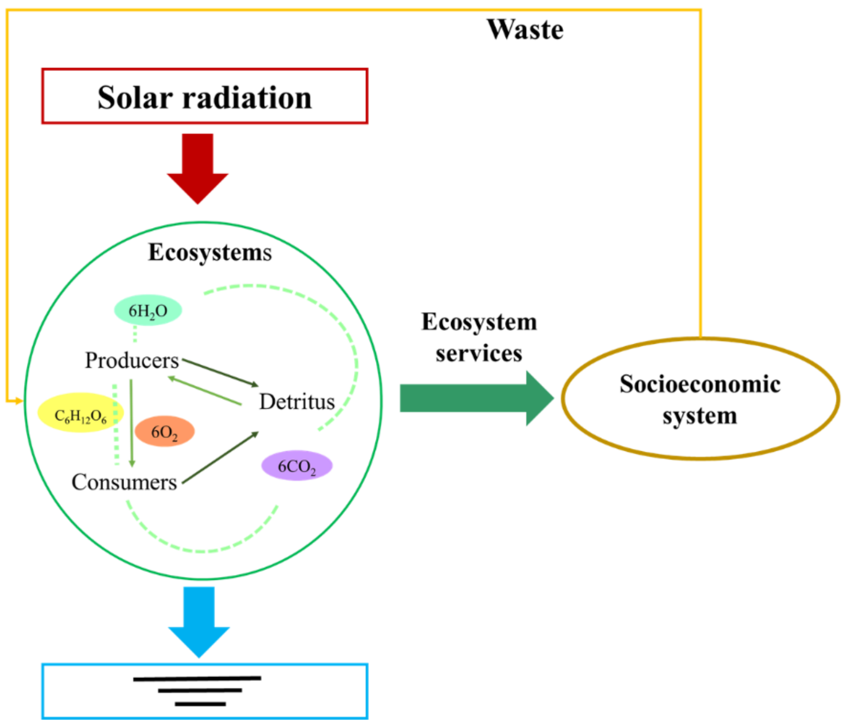

Figure 2. Socio-ecological systems, interactions between environmental processes and socioeconomic systems. The energy from solar radiation supports the maintenance and operation of ecosystems from the structure and organization of the species (photosynthesis

and cellular respiration) that are considered energy stores (ecoexergy) which support the generation of natural capital or ecosystem services used by the socioeconomic systems.

Additionally, these studies highlight how ecosystems are the environmental part of the socio-ecological systems (human-environment systems) with specific behaviors and, consequently, a specific evolution that, given the self-regulation of the ecosystem activity, will acquire low-entropy configurations [54,55].

Thus, these socio-ecological systems are formed from constant interactions between biophysical and social factors, which take place at different spatial, temporal and organizational scales (Figure 2). The variables that link ecosystems and human components are the so-called ecosystem services, which are defined as benefits that people obtain from ecosystems, and their valuation can be used either as an indicator of the yield or useful production of such systems [1,56].

From the previous ideas, it follows that the development of EScs, which recognizes the immersion of environmental problems in the social dynamics, allows for the classification of ecosystems in a socio-ecological context through the evaluation of the social value of ecosystem services in conjunction with complementary indicators such as ecoexergy. It is expected then that the functionality of an ecosystem can always be oriented towards a high ecoexergy, this is, a prominent capacity to perform useful work that is reflected in the quality of ecosystem services [26].

In short, the interdisciplinarity of ESc that admits the meeting of efforts from various disciplines has made it possible to implement innumerable advances in research that quantify, to a certain extent, the capacity of an ecosystem to provide services to the society [1,57]. Thus, it is possible to appreciate how ecosystems work and how ecosystem services are derived directly from the natural functions considered in biomass and increases in ecoexergy.

7. Conclusions

To recognize that the behavior and processes of an ecosystem are linked to social dynamics also implies recognizing the adjacent complexity in the study of environmental and anthropogenic interrelationships that can only be addressed through joint efforts in common dialogue in either an interdiscipline or transdiscipline. Thus, to see the exergy as a result of interdisciplinarity shows that the laws that describe the behavior of an ecosystem are based on thermodynamic laws, which eventually made the use of a specific equation such as ecoexergy possible in order to understand essential aspects in the functioning of socioecological systems immersed in the input-state-output flow dynamics.

This is demonstrated by the growing variety of studies that reveal the description of the system in terms of matter, energy, structural and functional problems, as well as its performance, understood as the diversity of ecosystem services provided [19].

However, the challenges and limits of the incorporation of the ecoexergy theory in the Esc are recognized since, despite the attempts in the search for interdisciplinary and transdiscipline, most of the environmental investigations culminate in multidisciplinary studies due to the lack of common concepts and methodologies. This is urged in the configuration of an epistemological approach with a theory that provides conceptual frameworks, models, laws and methods [49].

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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