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Entropy Analysis of the Coupled Human–Earth System: Implications for Sustainable Development

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Abstract: Finding the basic physical foundation contributing to sustainable development is significantly useful in seeking ways to build an enduring human future. This paper introduces the dissipative structure theory to analyze the entropy budgets of the whole coupled human–Earth system and the key processes of the subsystems, and then presents the formulas to calculate these entropy budgets. The results show that the total net negative entropy of the coupled human–Earth system from exchange with space is sufficient, but only about 0.0042% of it is available for sustaining the life activities of the whole coupled system and the quantity of this portion is also not more than sufficient compared with the requirement of human life activities. In addition, the rate of negative entropy consumption by human subsystem from fossil fuels for sustaining modern civilization is too large, nearly a half of the negative entropy rate obtained by photosynthesis on the Earth, which indicates that entirely substituting biomass fuels for fossil fuels may be infeasible. The strategies for sustaining human life activities and modern civilization are proposed in the study, which would provide valuable information for humans to realize sustainable development.

Keywords: entropy flux; negative entropy; thermodynamics; dissipative structure theory; sustainable development

1. Introduction

Since the term of sustainable development was widely articulated in the 1980s, it has risen rapidly in the public consciousness and the academic focus [1–5], and from that time on people have been seeking ways to forge new relationships between humans and nature [6–11], for gaining broad prosperity and a better way of life without environmental pollution, habitat destruction and species extinction. Today, Sustainable development is widely recognized as a new revolution of human society and increasingly being regarded as a vital strategy to build an enduring human future.

From a perspective of thermodynamic physics, a system can sustain a state away from thermodynamic equilibrium due to exchanges of energy and/or mass with its surroundings. The processes of the exchanges follow the laws of thermodynamics, of which the first law quantifies how much work can be extracted from heat according to the law of conservation of energy, and the second law introduces the function of entropy to describe the state of a system that the change of entropy tells us about the irreversibility of processes, thereby providing us with the direction about the arrow of time.

Generally speaking, the notion of entropy can be understood as a measure of disorder within a macroscopic system. Based on the second law of thermodynamics, the calculation of the entropy changes in a system and the entropy exchanges with its surroundings can provide information on the trends and evolution of the system [12]. This makes entropy analysis become a widely used method and be introduced into many fields of studies [13–18] and many types of systems [19–23]. With the extensive application of the thermodynamics theory, many studies have focused on non-equilibrium thermodynamics of the Earth [24–28], and the relevance of the laws of thermodynamics for realizing social and environmental sustainability has been gradually noted [29–32].

The Earth has an exchange of energy with space by receiving radiation from the Sun and emitting terrestrial long-wave radiation. This radiative exchange maintains the Earth in the non-equilibrium state, such as the composition of the atmosphere, the hydrologic cycle, and the carbon cycle. Peixoto et al. [33] showed that the mean outgoing flux of long-wave radiation to space equals the incoming flux of solar energy almost exactly in a long-term scale, but the corresponding mean outgoing flux of entropy is much larger than the mean incoming flux of entropy through solar radiation. It could be claimed that the net negative entropy influx from radiative exchange makes the various irreversible natural processes occur and operate on the Earth, including the development and succession of life and ecosystem. If the average rate of entropy production by the Earth does not exceed the average rate of negative entropy potential from the sun, the entropy of the whole Earth would be not increasing and the disorder would not become greater. This way, the Earth seems to be sustainable.

However, the Earth and the human society nowadays are tightly coupled. Humans depend on the Earth and its ecosystems for a wide range of goods and services, and dump the wastes into land, water and the atmosphere. A convenient way to conceptualize the above relationship is considering the Earth as the sources and the sinks. Human activities are between taking from sources and depositing as waste materials and emissions to sinks [34]. Meanwhile, humans have remarkable and great influence on the land surface and the natural cycles of the Earth such that the future state of the Earth is also dependent on humans. This interdependence makes our planet becoming a coupled human–Earth system. Just analyzing the entropy of the whole planet is far from enough to provide sound information for sustainability.

That the entropy of the whole system is not increasing is just a primary requirement for sustainability. Actually, only if the entropy of each subsystem or system component on the Earth is not increasing can the system of planets maintain a sustainable state. Realizing that the entropy is a global property of a system, Fisher Information, which describes the local property of a system and is more sensitive to perturbations, is introduced to measure the sustainable state of complex systems [35,36]. However, calculation of the Fisher Information needs to select proper state variables and determine a probability distribution of finding the system in a particular state. The interpretation of the Fisher Information in terms of real complex systems and the application of the method to analyze the state of the complex giant system like coupled human–Earth system need further work [37]. Therefore, this study focuses on the thermodynamic entropy changes of the key subsystems and processes of the coupled human–Earth system as it is common that the degradation of one of the key subsystems would induce the degradation of the whole system.

Accordingly, this paper introduces the theory of dissipative structure to characterize the entropy variation about the whole coupled human–Earth system and its subsystems. The boundary defined between the coupled human–Earth system and its surroundings is the top of the atmosphere, and the boundaries between the subsystems are based on the processes of mass and energy exchanges as the subsystems are highly coupled, thereby making it difficult to provide the definite physical boundaries. The details of the definition are given in Sections 2.2 and 2.3. The emphasis of the study is on the net entropy influx of key processes of these systems from exchanges with their surroundings, which can give an understanding and quantification of underlying general directions into which key processes within or between the subsystems of the coupled human–Earth system evolve in time. These directions can help us deal with the relationship of humans and nature and are thereby essential for achieving sustainable development. The entropy flux exchanges of these processes are characterized by constructing a framework of entropy flow according to matter flows and heat flows, and furthermore, the formulas to calculate these entropy budgets from exchanges are presented. The entropy budgets would provide basic physical foundation information contributing to sustainable development, and provoke humans into thinking about the pattern of the social development and the manner of human behaviors, and thereby seek paths to realize the strategy of sustainable development.

2. Methods

2.1. Dissipative Structure Theory

In physical science, there are three types of thermodynamic systems: isolated systems with exchange of neither energy nor mass taking place with the surroundings, closed systems exchanging energy but no mass with the surroundings, and open systems that exchange both energy and mass with the surroundings. Classical thermodynamics focus on isolated systems which tend toward the state of thermodynamic equilibrium with maximum entropy according to the second law of thermodynamics. However, the coupled human–Earth system is a non-equilibrium system with highly complex and ordered structures.

To explain the growth and evolution of the system far from equilibrium, the theory of dissipative structure [38,39], a developed version of the second law, is introduced to characterize the entropy variation of a system, dS, which is given by

$$\frac{dS}{dt} = \frac{d_i S}{dt} + \frac{d_e S}{dt} \quad (1)$$

where dt denotes the time period; $d_i S$ is the entropy produced by the processes inside the system; $d_e S$ is the net entropy influx from exchange with the surroundings. While $d_i S$ is always non-negative, $d_e S$ can be positive or negative depending on entropy exchange between the system and the surroundings, obviously zero for an isolated system.

There are three possibilities for entropy budget in a non-isolated system: (1) $dS/dt > 0$, (2) $dS/dt < 0$, or (3) $dS/dt = 0$. In the first situation, the system loses order; in the second situation, the system gains order, evolving toward a more ordered state; and in the third situation, the system maintains a steady state. Thus, $dS/dt \leq 0$ is the essential requirement for a system to further develop its structure and maintain ordered. This case is only possible when

$$\frac{d_e S}{dt} \leq -\frac{d_i S}{dt} \leq 0 \quad (2)$$

It means that the system must get a sufficient net influx of negative entropy to offset the internal entropy generation. Otherwise the system will tend toward thermodynamic equilibrium and eventually collapse.

2.2. Entropy Budget of the Coupled System from Exchange with Space

To analyze the entropy of a system, the boundaries of the system need to be defined firstly. The different choices of the boundaries determine the different types of thermodynamic systems, in that different types of exchange fluxes through the boundaries need to be considered. In this work, the choice for the boundary of the coupled human–Earth system distinguished from its surroundings is the top of the atmosphere, which is also recommended by Kleidon [40]. There, the dominant exchange is radiative, with low entropy solar radiation entering the coupled human–Earth system and terrestrial long-wave radiation as well as some scattered solar radiation being returned to space. Consequently, the coupled human–Earth system can be considered to be a closed system in that the relatively small exchange of matter with space owing to gravity and mass is negligible.

The radiation emitted by the Sun and by the Earth can be both considered as black-body radiation. As to a black body, the flux rates of energy (J_{QR}) and entropy (J_{SR}) with radiation emitted per unit surface area in terms of its thermodynamic temperature T are given by [41]

$$J_{QR} = \sigma_B T^4 \quad (3)$$

and

$$J_{SR} = \frac{4}{3}\sigma_B T^3 \quad (4)$$

where

$$\sigma_B = \frac{2\pi^5 k^4}{15c^2h^3}. \tag{5}$$

Here, k is the Boltzmann's constant; c is the speed of light in a vacuum; h is the Planck's constant; σ_B is called the Stefan–Boltzmann constant, and has a value of 5.67×10^{-8} W/(m^2·K^4). Therefore, the relationship between entropy emission (dS_R) and heat transfer (dQ_R) of the black body can be expressed as

$$dS_R = \frac{4}{3}\frac{dQ_R}{T} \tag{6}$$

Solar radiation was emitted from the surface of the Sun. When it arrives at the Earth, its flux density is diluted into a sphere with a radius of the distance from the Sun to the Earth.

Base on Equation (3), the solar radiative flux rate at the top of the Earth atmosphere is given by

$$J_{QSE} = \frac{4\pi R_S^2 \sigma_B T_S^4}{4\pi r_{SE}^2} = \left(\frac{R_S}{r_{SE}}\right)^2 \sigma_B T_S^4 \tag{7}$$

where R_S is the solar radius with a value of about 6.957×10^5 km, r_{SE} is the distance between the Sun and the Earth with a mean value of 1.496×10^8 km, and T_S is the surface temperature of the Sun, approximated to be 5780 K.

However, the Earth has an albedo α of 0.3 [42], with about 30% of the incoming solar radiation without absorption for reflected and scattered back into space by the clouds within the atmosphere and the reflective surfaces at the ground. The radiative flux rate of the Earth absorbing should be discounted. Additionally, the solar radiant energy on the Earth is unevenly distributed, and it varies in intensity with the latitude. A multibox model, which is originally presented by Paltridge [43], would be suitable to analyze the energy exchange of the Earth. In this work, the Earth is divided into 5 latitude zones as depicted in Figure 1. The division are corresponding to the division of the geographical zones which comprise North Frigid Zone, North Temperate Zone, Torrid Zone, South Temperate Zone and South Frigid Zone. As the subsolar point on the Earth moves north and south over the course of a year, the absorbed solar radiation of each zone varies with the season. Thus, the average rate of the solar energy absorbed by each zone in the four seasons is used as the input rate of the solar energy. For zone i, it is given by

$$q_{i,in} = \frac{dQ_{i,in}}{dt} = \frac{1}{4}\sum_{j=1}^{4}(1-\alpha)A_{p,ij}J_{QSE} \tag{8}$$

where $A_{p,ij}$ is the projected area of the zone i in the jth season as seen by the Sun. As for projection analysis and calculation, that the subsolar point is on the equator in the spring, the latitude of 23°26′ N in the summer, the equator in the autumn, and the latitude of 23°26′ S in the winter is used in this paper. The mean value of the Earth radius is 6371 km. Accordingly, the surface areas of the zones and the projected areas in four seasons are listed in Table 1.

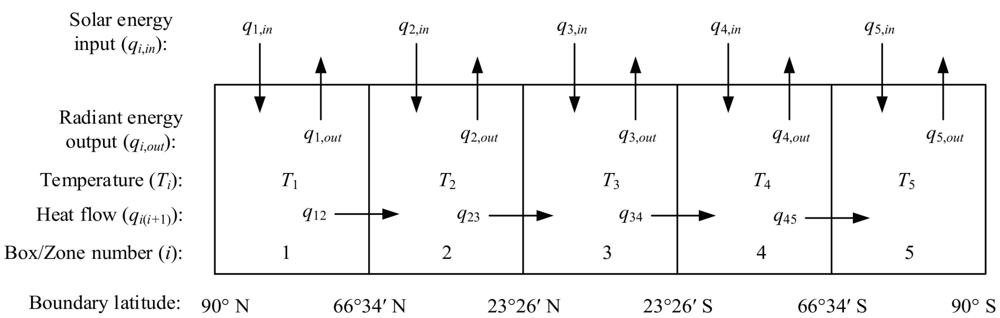

Figure 1. Multibox model with five latitude zones of the Earth.

Table 1. Surface areas and projected areas of the latitude zones.

Zone Number	Surface Area(km^2)	Projected Area (km^2)			
		Spring	Summer	Autumn	Winter
1	21,033,596.8	1,790,192.4	8,019,634.6	1,790,192.4	0.0
2	132,578,334.3	30,557,112.4	48,108,964.0	30,557,112.4	13,438,080.8
3	202,840,609.8	62,821,508.5	57,949,438.5	62,821,508.5	57,949,438.5
4	132,578,334.3	30,557,112.4	13,438,080.8	30,557,112.4	48,108,964.0
5	21,033,596.8	1,790,192.4	0.0	1,790,192.4	8,019,634.6

Based on Equation (3), the radiant energy rate emitted by box *i* of the Earth can be given by

$$q_{i,out} = \frac{dQ_{i,out}}{dt} = A_{s,i}\sigma_B T_i^4 \tag{9}$$

where $A_{s,i}$ is the surface area of the zone *i*, and T_i is the effective temperature of the box *i*. There are energy flows between the boxes. Suppose that heat transport were purely due to sensible heat by meridional winds. Then the heat flow from box *i* to box *i* + 1 can be given by

$$q_{i(i+1)} = \rho C_p v A_{b,i(i+1)}(T_i - T_{i+1}) \tag{10}$$

where ρ is the surface atmospheric density with a value of 1.25 kg/m^3; C_p is the heat capacity of the air with a value of 1.00 kJ/(kg·K); v is the average meridional wind velocity with a value of about 0.5 m/s; $A_{b,i(i+1)}$ is the boundary area between box *i* and box *i* + 1, which can be calculated by

$$A_{b,i(i+1)} = \pi\left[(R_E + H)^2 - R_E^2\right]\cos\theta_{i(i+1)} \tag{11}$$

where R_E is the radius of the Earth; H is the height of the troposphere with an average value of 10 km; and $\theta_{i(i+1)}$ is the boundary latitude between box *i* and box *i* + 1.

Considering the symmetry of the multibox model (Figure 1), it is obvious that $T_1 = T_5$, $T_2 = T_4$, $q_{12} = -q_{45}$ and $q_{23} = -q_{34}$. Accordingly, the energy balances with respect to box 3, box 4 and box 5 are

$$q_{3,in} = A_{s,3}\sigma_B T_3^4 + 2\rho C_p v A_{b,34}(T_3 - T_4) \tag{12}$$

$$q_{4,in} = A_{s,4}\sigma_B T_4^4 - \rho C_p v A_{b,34}(T_3 - T_4) + \rho C_p v A_{b,45}(T_4 - T_5) \tag{13}$$

and

$$q_{5,in} = A_{s,5}\sigma_B T_5^4 - \rho C_p v A_{b,45}(T_4 - T_5) \tag{14}$$

The above three equations are closed as they contain only three unknowns, T_3, T_4 and T_5. Therefore, the temperatures of the boxes of the model can be solved. Then, the net entropy influx of box *i* from exchange with the space is

$$\frac{d_e S_{i,space}}{dt} = \frac{4}{3}\left(\frac{1}{T_S}\cdot\frac{dQ_{i,in}}{dt} - \frac{1}{T_i}\cdot\frac{dQ_{i,out}}{dt}\right) = \frac{4}{3}\left(\frac{q_{i,in}}{T_S} - \frac{q_{i,out}}{T_i}\right) \tag{15}$$

Therefore, the net import of entropy flux of the coupled human–Earth system from the surroundings is given by

$$\frac{d_e S_E}{dt} = \sum_{i=1}^{5}\frac{d_e S_{i,space}}{dt} = \frac{4}{3}\sum_{i=1}^{5}\left(\frac{q_{i,in}}{T_S} - \frac{q_{i,out}}{T_i}\right) \tag{16}$$

2.3. Entropy Exchange Framework on the Processes of the Subsystems

To analyze the entropy flow and budget inside the coupled human–Earth system, this work decomposes the coupled human–Earth system into human subsystem, biotic subsystem, and abiotic subsystem. The analysis of the entropy fluxes with respect to these subsystems would be beneficial to finding the problems against the sustainability of the whole coupled system.

Human subsystem encompasses humans and human activities, artificial structures and artificial environments. Biotic subsystem is a community of living organisms (plants, animals, microbes, etc.) without humans, including the activity and interaction of these living organisms. Abiotic subsystem encompasses all things in nature excluding the life on the Earth, like air, water, and mineral soil. Then, the flows of energy and mass make the above three subsystems linked to an entirety.

The solar energy drives atmospheric circulation and hydrological cycle in abiotic subsystem. The atmospheric circulation—the large-scale movement of air—causes the motion of the masses of air and the redistribution of the energy absorbed by the Sun. The hydrological cycle—the continuous movement of water on, above and below the surface of the Earth—involves the exchange of energy, the transportation of minerals across the globe, and reshaping the geological features of the Earth through the physical processes of evaporation, condensation, precipitation, infiltration, surface runoff and subsurface flow. The above movements within the abiotic subsystem are helpful in moving matters in large scale and essential for the maintenance of most life and ecosystems.

As to the biotic subsystem, the solar energy enters the system and is converted into chemical energy through photosynthesis, which also captures carbon from the abiotic subsystem. Plants and microbes of the biotic subsystem also use the nutrients from the abiotic subsystem. In the meantime, microbes break down dead organic matter with releasing carbon and converting nutrients back to the abiotic subsystem.

Human subsystem, the most influential subsystem of the coupled human–Earth system, feeds on food supplied by the productivity of the biotic subsystem and extracts materials from the biotic subsystem and the abiotic subsystem. Then, the human subsystem rejects the wastes into the abiotic subsystem. In this study, that the wastes produced by the human subsystem flow into the biotic subsystem is considered to be not direct, but by the transit of the abiotic subsystem. The above behaviors of the human subsystem have significant influences on the structures and functions of the other two subsystems, and play a dominant role in the entire coupled human–Earth system. The two main paths of the flows of the mass and the energy associated with the human subsystem from exchange with the other two subsystems is illustrated in Figure 2.

Since the subsystems of the coupled human–Earth system are highly coupled with each other, it is difficult to give the definite physical boundaries between the subsystems. Thus, the boundaries are defined based on the processes of mass and energy exchanges. More specifically, the boundary between the biotic subsystem and the human subsystem is before the processes of humans using the matters and the energies which are produced by the biotic community; the boundary between the human subsystem and the abiotic subsystem is before the processes of humans using the materials and the energies extracted from and after the processes of humans discarding the waste matters and energies to the abiotic nature environment. Similarly, the boundary between the biotic subsystem and the abiotic subsystem is before the processes of the matters and the energies of the abiotic nature environment flowing into the living organisms (without humans) and after the processes of the living organisms releasing the matters and the energies to the abiotic nature environment. With the flows of mass and energy crossing the boundaries of the subsystems, there are underlying exchanges of entropy between each other. These exchanges are illustrated in Figure 3.

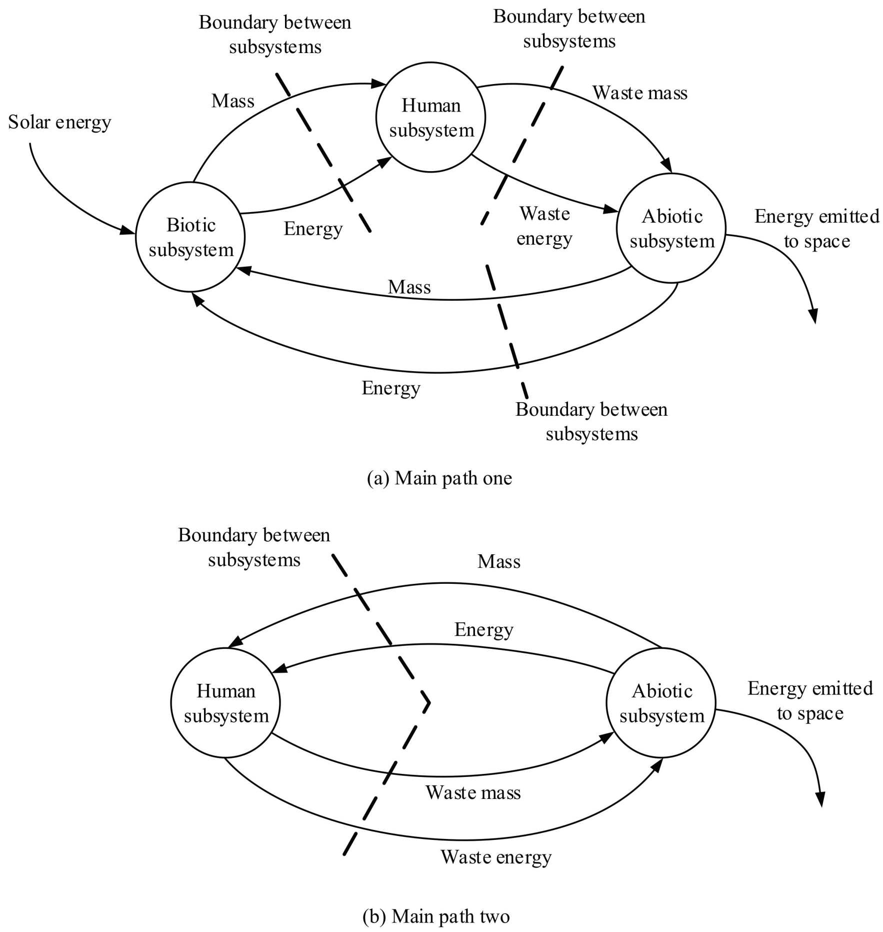

Figure 2. Two main paths of the flows of mass and energy exchanges associated with the human subsystem.

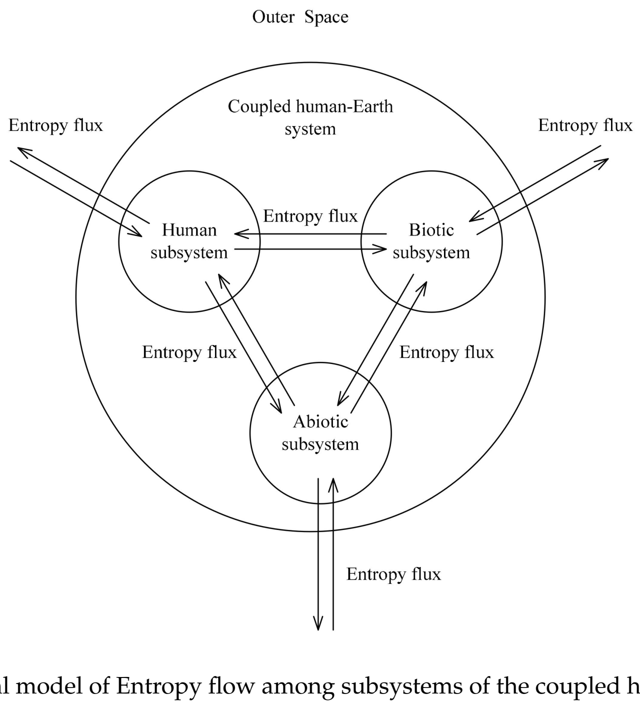

Figure 3. Conceptual model of Entropy flow among subsystems of the coupled human–Earth system and the outer space.

Usually, the processes in which heat and work are transferred are considered separate from the processes for transfer of matter in a thermodynamic system. Although there are some processes in which both heat and matter are transferred, these processes can be decomposed into separated processes associated with the transfers of heat and matter respectively for the purpose of thermodynamic analysis. Thus, the net entropy exchange rate of any process (denoted by X) of the subsystems is expressed as

$$\frac{d_e S_X}{dt} = \sum_k \hat{S}_k \frac{dm_k}{dt} + \sum_j \frac{\gamma_j}{T_j} \cdot \frac{dQ_j}{dt} \tag{17}$$

where $\hat{S}_k$ is the entropy per unit of the kth matter; m_k is the quantity with respect to the flow of the kth matter, with a negative value if the matter flows out of the system; Q_j is the jth heat flow and T_j is the temperature corresponding to the flow; γ_j is the factor associated with the transfer way of the jth heat flow, γ_j = 1 for heat conduction while γ_j = 4/3 for heat radiation.

2.4. Entropy Budget of the Biotic Subsystem from Sunlight

The negative entropies for sustaining life activities of the biotic subsystem and the human subsystem both come from sunlight through the process of photosynthesis, which is mainly performed by photoautotrophs such as most plants, most algae, and cyanobacteria in the biotic subsystem. Photosynthesis is a complicated process. It occurs in two stages. In the first stage, light-dependent reactions capture the energy of light and use it to make the energy-storage molecules ATP and NADPH. During the second stage, the light-independent reactions use these products to capture carbon dioxide from atmosphere and reduce it to carbohydrate. The overall equation for the type of photosynthesis that occurs in plants can be expressed as

$$6CO_2 + 6H_2O \xrightarrow{hv} C_6H_{12}O_6 + 6O_2 \tag{18}$$

The changes of standard enthalpy and entropy in the reaction (per mole glucose) respectively are

$$\Delta H_g = 2.802 \times 10^6 \text{ J/moL} \tag{19}$$

and

$$\Delta S_g = -585.8 \text{ J/(moL·K)} \tag{20}$$

It means that photosynthesis can obtain the negative entropy −585.8 J/K at 298.15 K when absorbing the photo energy 2.802 × 10^6 J from the sunlight.

However, most of the solar radiation energies coming into the Earth were absorbed by the atmosphere and for the evaporation of the water. The mean ratio β of the energy absorbed by the photosynthesis to the energy of solar radiation incident on the surface of the Earth for all the year in the whole Earth is about 0.1% [44]. Therefore, the net negative entropy that the biotic subsystem obtains from the sunlight is given by

$$\frac{d_e S_{Bs}}{dt} = \beta \cdot q_{E,in} \cdot \frac{\Delta S_g}{\Delta H_g} \tag{21}$$

where $q_{E,in}$ is the rate of the solar energy absorbed by the whole Earth. Accordingly, the entropy above is the total negative entropy obtained by the photosynthesis on the Earth, which is stored in the products of the photosynthesis (carbohydrates) and then is available for sustaining life activities of the biotic subsystem and the human subsystem.

2.5. Entropy Budget Associated with Life Activities of the Human Subsystem

Human life activities are sustained by feeding on foods. The carbohydrates in foods are oxidized in the process of respiration, which can be considered as the inverse process of the photosynthesis.

Thereby, humans can get the energy and the negative entropy which are ΔH_g and ΔS_g (per mole glucose) to maintain the structures and functions of the organism based on Equations (13) and (14). Accordingly, the negative entropy associated with life activities of the human subsystem is given by

$$\frac{d_e S_{Hf}}{dt} = P \cdot \frac{m_g}{M_g} \cdot \Delta S_g \tag{22}$$

where P is the world population; m_g is the average mass rate of glucose consumption per person as all foods are converted into glucose; M_g is the molar mass of glucose, with a value of 180 g/moL.

2.6. Entropy Budget Associated with Fuels Use of the Human Subsystem

Humans burn fuels to produce useful output energy which is mechanical work or heat, or possibly both. During the process, fuels burn to generate heat at a high temperature and the residual heat is released to the environment at a low temperature. Then, the negative entropy flows into the human subsystem. This negative entropy is mainly used for maintaining the normal operation of human modern civilization, including industrial activities, transportation and social activities. Its budget can be calculated by

$$\frac{d_e S_{Hb}}{dt} = \frac{1}{T_h} \cdot \frac{dQ_h}{dt} - \frac{1}{T_c} \cdot \frac{dQ_c}{dt} = \frac{1}{T_h} \cdot \frac{dQ_h}{dt} - \frac{1}{T_c} \cdot \frac{(1-\eta)dQ_h}{dt} = \frac{dQ_h}{dt}\left(\frac{1}{T_h} - \frac{1-\eta}{T_c}\right) \tag{23}$$

where Q_h is the heat generated by fuels burning; T_h is the temperature while fuels are burning; η is the thermal efficiency representing the ratio between the useful output energy and Q_h; Q_c is the heat released to the environment, the ratio of which to Q_h is $1 - \eta$ since the proportion of the Q_h converted to useful output is η; T_c is the temperature when the heat is released to the environment.

3. Entropy Budget Calculation Results

3.1. Negative Entropy of the Whole Coupled System from Exchange with Space

Based on Equation (7), the solar radiative flux rate at the top of the Earth atmosphere is 1368.6 W/m^2. Then, based on Equation (8), the input rate of the solar energy with respect to each zone depicted in Figure 1 can be calculated. Afterwards, combining the Equations (12)–(14), the effective temperatures of the boxes can be solved. Finally, the radiant energy rate emitted by the zones and the net entropy influxes of the zones from exchange with the space are obtained, respectively, based on Equations (9) and (15). The calculation results are shown in Table 2. Indicated by Table 2, the solar energy rate absorbed by the whole Earth, which is the total of all the zones, is 1.222×10^{17} W, and the total net negative entropy flux flowing into the coupled human–Earth system is -6.102×10^{14} W/K based on Equation (16). In comparison with the previous study, the net negative entropy flowing into the Earth presented by Kleidon [24] is -918 mW/(m^2·K). Accordingly, the total with respect to the coupled system is -4.682×10^{14} W/K. Multiplying this value by the coefficient of 4/3 associated with the radiation of the black body as shown in Equation (6) makes -6.243×10^{14} W/K, which the result presented in this paper approximately equals.

Table 2. Calculation results of the thermodynamic parameters of the multibox model.

Zone Number	Absorbed Solar Energy (W)	Effective Temperature (K)	Emitted Radiant Energy (W)	Net Entropy Import from Space (W/K)
1	2.7783×10^{15}	240.1	3.9637×10^{15}	-2.1370×10^{13}
2	2.9378×10^{16}	252.0	3.0320×10^{16}	-1.5364×10^{14}
3	5.7850×10^{16}	261.3	5.3595×10^{16}	-2.6016×10^{14}
4	2.9378×10^{16}	252.0	3.0320×10^{16}	-1.5364×10^{14}
5	2.7783×10^{15}	240.1	3.9637×10^{15}	-2.1370×10^{13}

Furthermore, Table 3 gives the ratio of thermodynamic fluxes of the zones to that of the whole Earth. It shows that Zone 3 (Torrid Zone), covering 39.8% of the surface of the Earth, accounts for nearly a half of the absorbed solar energy, and 42.6% of the net negative entropy influx from exchange with space. In addition, Zone 2 (North Temperate Zone), Zone 3 (Torrid Zone), and Zone 4 (South Temperate Zone) altogether account for 93.0% of the net negative entropy influx from space.

Table 3. The ratio of surface areas and thermodynamic fluxes of the zones to that of the whole Earth.

Zone Number	Surface Area (%)	Absorbed Solar Energy (%)	Emitted Radiant Energy (%)	Net Entropy Import from Space (%)
1	4.1	2.3	3.2	3.5
2	26.0	24.0	24.8	25.2
3	39.8	47.4	43.9	42.6
4	26.0	24.0	24.8	25.2
5	4.1	2.3	3.2	3.5

3.2. Negative Entropy for Sustaining Life Activities of the Whole Coupled System

Based on Equation (21), the net negative entropy flux flowing into the biotic subsystem through the process of photosynthesis, the total negative entropy for sustaining life activities of all living organisms on the Earth, including plants, animals and humans, is -2.554×10^{10} W/K. It means that only about 0.0042% of the total net negative entropy flux flowing into the Earth can be used for sustaining the life activity of the whole coupled human–Earth system.

3.3. Negative Entropy Associated with Life Activities of the Human Subsystem

The foods that one person needs per day counted by glucose is about 1.0 kg. There are about 7.5 billion people on the Earth today. Based on Equation (22), the negative entropy needed to sustain the life activities of the human subsystem is about -2.825×10^{8} W/K. It seems that there is sufficient negative entropy for sustaining the life activity of humans, since the value of the negative entropy for sustaining life activities of the whole coupled system is nearly one hundred times this value. However, there are many trophic levels in the biotic subsystem, and the ecological efficiency, representing the efficiency of the energy or biomass transfer between one trophic level and the next, is generally 10%. Hence, for the trophic level 2 that herbivores at the negative entropy budget for sustaining life activities is about -2.554×10^{9} W/K, and for the trophic level 3, this budget is only about -2.554×10^{8} W/K. Humans feed at trophic levels from 2 to 5, and most of the primary producers (trophic level 1) on the Earth could not provide foods for humans directly or indirectly. It is evident that the negative entropy for supporting the human life activities is not abundant.

3.4. Negative Entropy Associated with Fossil Fuels Used by Human Subsystem

Referring to the energy consumption in 2014, the energy use per capita of the world is 1929.4 kg of oil equivalent, which is equivalent to 8.0780×10^{10} J, and the fossil fuel energy consumption is 80.805% of the total energy use (data from the World Bank, http://data.worldbank.org). The average temperature of the fossil fuel burning is about 1500 K, and the average temperature of the heat released to the environment is about 500 K. In the meantime, the average thermal efficiency is about 30%. Based on Equation (19), the negative entropy flowing into the human subsystem from use of fossil fuels is -1.138×10^{10} W/K, which is used for sustaining human modern civilization. Obviously, the consumption rate of this negative entropy is very large. Most importantly, it is not contained in the total net negative entropy influx of the whole couple system from exchange with space nowadays. It comes from the storage in the Earth and is non-renewable.

4. Implications for Sustainable Development

As shown by the calculation results, the total net negative entropy budget of the coupled human–Earth system is sufficient. However, the negative entropies available for key processes of the subsystems, such as life activities of the biotic subsystem and the human subsystem and the modern civilization functioning of the human subsystem, are not very abundant or even seriously deficient. Implied by the dissipative structure theory, these subsystems of the coupled human–Earth system are at great risk of degradation due to the lack of plentiful negative entropy.

In the total negative entropy budget, the corresponding portion that can be used for sustaining life activities of the whole coupled system is too small (about 0.0042% of the total), and is also not more than enough compared with the negative entropy requirement associated with human life activities when considering that the ecological efficiency is not high. Thus, to sustain the life activity of humans, great efforts should be taken to develop agricultural technology and protect agricultural land resources, making more negative entropy flow into crops and plants from the sunlight. In the meantime, population size must be controlled. Let population grow with no limits, and it is doubtful that there are enough foods to feed the people of the world in the future.

The negative entropy from fossil fuel burning, used for human modern civilization functioning, is with a limited total quantity on the Earth. It becomes less and less as people have been using it. Actually, this negative entropy comes from ancient photosynthesis, typically millions or even hundreds of millions of years ago. When it is used up, how to sustain the modern civilization of humans is still an open question. Using biomass fuels, which are renewable, may be an alternative. However, the negative entropy consumption rate of the human subsystem from fossil fuel use is too large, nearly a half of the net negative entropy rate obtained by the photosynthesis on the Earth. Therefore, entirely substituting biomass fuels for fossil fuels is hard to continue. If the human subsystem extracts too much negative entropy from the biotic system that the negative entropy flux flowing into the biotic subsystem could not maintain its development or even the net entropy influx is positive, the biotic system would be degraded.

Thus, to realize sustainable development of the human civilization and the environment, the key is to find new negative entropy sources substituted for fossil fuels. In fact, the negative entropy consumption rate associated with fossil fuels is only about 0.0019% of the total net negative entropy budget of the coupled human–Earth system from exchange with space. If humans can effectively use the negative entropy from the sunlight directly with taking out many intermediate processes, there would be enough negative entropy to sustain the modern civilization. This might be the ultimate way to achieve sustainability of the human civilization. So devoting great efforts to developing solar energy technology and promoting solar energy utilization is essential for sustainable development. In addition, nuclear energy is also a useful supplement to the energy for human use.

5. Conclusions

In light of the views of the dissipative structure theory, this paper analyzed the entropy budgets of the whole coupled human–Earth system and the key processes of the subsystems with the purpose of providing sound information for sustainable development. It is clear that the total net negative entropy budget of the whole coupled system from exchange with space is sufficient. However, the negative entropy budget of the biotic subsystem obtained from sunlight, which is used for sustaining life activities of all the living organisms on the Earth, is not more than sufficient. Meanwhile, the consumption rate of the negative entropy associated with life activities of the human subsystem is relatively large when considering the ecological efficiency. This negative entropy is significant in connection of the human subsystem and the biotic subsystem, thereby making these two subsystems highly coupled, and is also the key that determines whether humans and the environment could be sustained. Implied by the budgets, humans should take great efforts to develop agricultural technology, protect agricultural land resources, and control the population size in order to obtain more negative entropy from the sunlight and constrain the growth of negative entropy extracted from biotic system, thus reducing and avoiding the environmental damage.

In addition, the negative entropy consumption rate of the human subsystem from fossil fuels is extremely large. To sustain the modern civilization of the human society, humans should devote great efforts to finding new negative entropy sources substituted for fossil fuels before they are used up. It may be infeasible to take biomass fuels as an absolute substitution for fossil fuels according to the entropy budget calculation results, while developing solar energy and nuclear energy may be a workable way to solve this problem. Only if there are adequate available negative entropies, which can be served to satisfy life activities and maintain modern civilization of the human subsystem, can the sustainable development of the coupled human–Earth system be realized in the future.

The limitation of this study is that only a few key processes within the coupled system are presented with entropy analysis, and the details of the entropy flow associated with these processes need to be further uncovered. These problems will be a focus of and discussed in the future work. Regardless of the limitation, however, the studies are encouraging.

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