Ecological Indicators 88 (2018) 37–42

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Transition from abstract thermodynamic concepts to perceivable ecological indicators

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ARTICLE INFO

Keywords:
Ecosystem development
Total entropy production
Exergy destruction
Specific entropy production
Surface temperature
Thermodynamics

ABSTRACT

Entropy and exergy are the central concepts in thermodynamics, and many researchers have used them to characterize ecosystem development. However, these concepts are very abstract to outsiders. Direct measurements of the indicators related to entropy and exergy are difficult and involve large errors. Schneider and Kay (1994) bridged thermodynamic concepts, i.e., entropy and exergy, with perceivable ecological indicators, i.e., canopy surface temperature (T_{surf}) and net radiation (R_n) in their maximum exergy destruction principle. However, the connection between entropy and exergy with T_{surf} and R_n was based on the similarity between the ecosystem and the Bénard cell, and not on thermodynamic reasoning. Considering the coherence of entropy production and exergy destruction, we analyzed the relationship between entropy production and T_{surf} and R_n, based on the first and second laws of thermodynamics, and verified it using long-term monitoring data of a tropical seasonal rain forest. We demonstrated that total entropy production (exergy destruction) linearly increased with increasing R_n and decreasing T_{surf} theoretically. Empirical data showed that the total entropy production increased, whereas specific entropy production decreased during the growing season. This indicates that plant growth can enhance exergy conversion efficiency. R_n, T_{surf}, and related indicators can be used as surrogates for thermodynamic indicators to measure ecosystem status and development. The bridge between thermodynamic concepts and measurable ecological indicators will improve the application of thermodynamics in ecology studies and the understanding of thermodynamic processes in ecosystem.

1. Introduction

The direction of ecosystem development (e.g., growth, succession, and recovery) has been a central theme in ecology study. It is not only a theoretical question, but also has implications for current environmental challenges, e.g., prediction of vegetation response to climate change or assessment of deforestation and restoration (Prach and Walker, 2011). Many patterns have been observed across ecosystem development, for example: the transition from r-selected species to K-selected species (MacArthur and Wilson, 1967), gross production/community respiration approaching one, life cycles and information increases (Odum, 1969), and the transition from quantity growth to quality growth (Fath et al., 2004). These measurements reflect the characteristics of ecosystems from a certain perspective. Thermodynamics, on the other hand, provides a comprehensive insight into system development (Chapman et al., 2016; Svirezhev, 2000). Entropy and exergy based concepts have been demonstrated to be useful to assess ecosystem development, and to integrally characterize ecosystems (Bejan, 2013; Bertram, 2014; Chapman et al., 2016; Fath et al., 2004; Fraser and Kay, 2002; Jørgensen, 2007; Kleidon, 2009). However, these thermodynamic concepts might not seem straightforward for ecologists who are not familiar with thermodynamics due to their relatively abstract ecological meaning.

Schneider and Kay (1994) connected thermodynamic concepts (i.e., exergy destruction) with ecological parameters in their maximum exergy destruction principle. They took ecosystems as dissipation structures that can dissipate temperature gradients more efficiently than bare ground. They emphasized that exergy destruction played key roles in ecosystem characterization, and the more developed ecosystems could gain more energy, while maintaining lower surface temperature (Fraser and Kay, 2002). Net radiation and canopy surface temperature are proxies for the interaction between vegetation and environment, which are perceivable ecological parameters and easy to be measured. Many experiments have supported Schneider and Kay' s conclusion

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https://doi.org/10.1016/j.ecolind.2018.01.001
Received 27 June 2017; Received in revised form 27 December 2017; Accepted 1 January 2018
Available online 02 February 2018

(Akbari, 1995; Lin, 2015; Lin et al., 2009; Lin et al., 2011; Maes et al., 2011); however, the Maximum Exergy Destruction principle was proposed based on the similarity between ecosystems and Bénard cells. Quantitative analysis of the relationship among exergy destruction, canopy surface temperature, and net radiation from the view of thermodynamic laws has never been conducted. According to the second law of thermodynamics, exergy destruction is actually proportional to entropy production (Cengel and Boles, 2014).

In the present study, we analyzed the relationship among entropy production (exergy destruction), net radiation, and canopy surface temperature based on thermodynamic laws, and verified it with long-term monitoring data of a tropical seasonal rain forest. We aim to further understand the relationships between thermodynamic concepts and ecological indicators, i.e., R_n and T_{surf}.

2. Materials and methods

2.1. Study sites

All the data were obtained from the meteorology gradient system on a tower in the tropical seasonal rain forest in Menglun, Xishuangbanna, southwestern China (21°57′N, 101°12′E, 750 m asl). The mean canopy height was 35 m. The annual mean temperature of this forest was 19.9 °C and the maximum air temperature was 34.6 °C. Annual precipitation averaged 1557 mm, 85% of which occurred during the rainy season (May–October). The dry season occurred from November to February (Cao et al., 2006).

2.2. Measurements

The net radiation was measured using a 4-component radiometer (CNR4, Kipp & Zonen, Netherlands) at 41.6 m above the ground. The canopy surface temperature was measured by an infrared thermometer (SI-111, Apogee, USA) installed at 52 m. We used the air temperature (HMP45C, Campbell Scientific Inc., USA) at the same height of the measurements of sensible heat (CSAT3, Campbell, USA) and latent heat (LI-7500, LI-COR Inc, USA) (48.8 m) in the calculation. Soil heat and soil temperature (105T, Campbell Scientific Inc., USA) were measured 5 cm below the soil surface. All variables were automatically sampled at 0.5 Hz, and 30 min averages were obtained as outputs from the data logger (CR5000, Campbell Scientific Inc., USA). For the detailed descriptions of the site and instruments, see Dou et al. (2007).

2.3. Data analysis

The average data from the year 2003 to 2009 were used in the present study. The total entropy production ($\dot{S}_{irrev}$) was calculated using the data at half-hour intervals. The daily total entropy production and net radiation were used to analyze seasonal courses. To analyze the relationship between entropy production and canopy surface temperature, we controlled the incoming shortwave radiation (K_{in}) at four levels: 600–610, 650–660, 700–710, and 800–810 J m^{-2} s^{-1}, and the incoming longwave radiation (L_{in}) within 450–460 J m^{-2} s^{-1} to satisfy the requirement of identical radiation environment.

3. Theory

According to the second law of thermodynamics, exergy destruction ($\dot{E}_d$) is proportional to entropy production (Cengel and Boles, 2014)

$$\dot{E}_d = T_0 \dot{S}_{irrev} \tag{1}$$

where T_0 is the temperature at the reference state, which can be taken as a constant. Therefore, exergy destruction is consistent with entropy production, and we only analyzed $\dot{S}_{irrev}$ in the present study.

The entropy budget $\left(\frac{dS}{dt}\right)$ (i.e., entropy change rate) of the ecosystem is calculated by entropy flux ($\dot{S}_{flux}$) and entropy production ($\dot{S}_{irrev}$) due to irreversible processes occurring inside the system:

$$\frac{dS}{dt} = \dot{S}_{irrev} + \dot{S}_{flux} \tag{2a}$$

Thereafter, entropy production is obtained as follows:

$$\dot{S}_{irrev} = \frac{dS}{dt} - \dot{S}_{flux} \tag{2b}$$

The energy storage rate of the ecosystem $\left(\frac{dE}{dt}\right)$ is determined by the temperature change and heat capacity of the ecosystem (Eq. (3)). In Eq. (3), C is the equivalent heat capacity of the whole forest. Considering the difficulty in measuring C, we calculated $\frac{dE}{dt}$ through energy balance. According to the first law of thermodynamics (i.e., energy conservation law):

$$\frac{dE}{dt} = C\frac{dT_{surf}}{dt} = K_{in} + L_{in} - K_{out} - L_{out} - H - LE - G - M \tag{3}$$

where, K_{in} is shortwave radiation, L_{in} is incoming longwave radiation, K_{out} is outgoing shortwave radiation, L_{out} is outgoing longwave radiation, H is sensible heat flux, LE is latent heat flux, G is soil heat flux, and M is energy flux owing to metabolic activity (Fig. 1). Usually, M is negligible because of the small magnitude (Gu et al., 2007).

The ecosystem can be considered an incompressible substance, therefore, the entropy budget in Eq. (2a) can be further expressed as (Cengel and Boles, 2014):

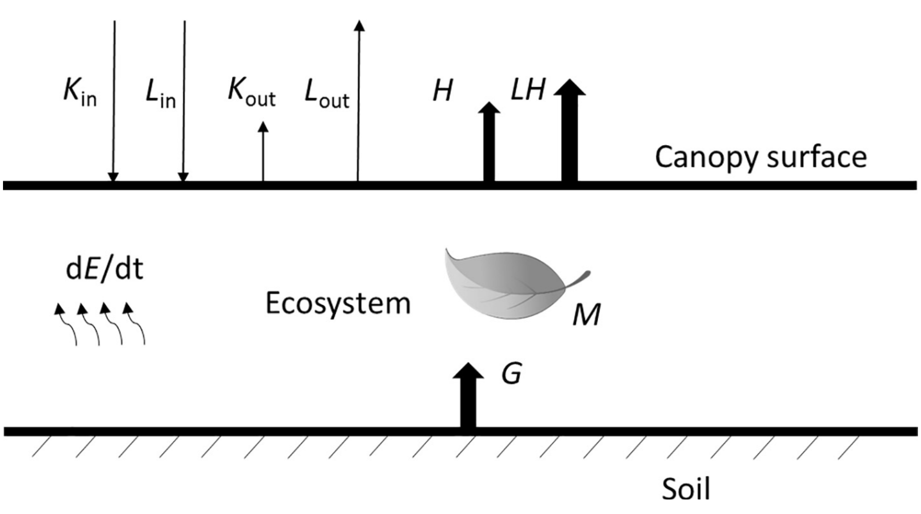

Fig. 1. Energy balance of ecosystem. K_{in}, incoming shortwave radiation; L_{in}, incoming longwave radiation; K_{out}, outgoing shortwave radiation; L_{out}, outgoing longwave radiation; H, sensible heat flux; LE, latent heat flux; G, soil heat flux; M, energy flux owing to metabolic activity; $\frac{dE}{dt}$, energy storage rate of ecosystem.