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Assessing self-organization of plant communities—A thermodynamic approach

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A B S T R A C T

Thermodynamics is a powerful tool for the study of system development and has the potential to be applied to studies of ecological complexity. Here, we develop a set of thermodynamic indicators including energy capture and energy dissipation to quantify plant community self-organization. The study ecosystems included a tropical seasonal rainforest, an artificial tropical rainforest, a rubber plantation, and two *Chromolaena odorata* (L.) R.M. King & H. Robinson communities aged 13 years and 1 year. The communities represent a complexity transect from primary vegetation, to transitional community, economic plantation, and fallows and are typical for Xishuangbanna, southwestern China. The indicators of ecosystem self-organization are sensitive to plant community type and seasonality, and demonstrate that the tropical seasonal rainforest is highly self-organized and plays an important role in local environmental stability via the land surface thermal regulation. The rubber plantation is at a very low level of self-organization as quantified by the thermodynamic indicators, especially during the dry season. The expansion of the area of rubber plantation and shrinkage of tropical seasonal rainforest would likely induce local surface warming and a larger daily temperature range.

1. Introduction

Scientists have long been interested in ecosystem development and its directionality (Lotka, 1922; Morowitz, 1968; Cheslak and Lamarra, 1981; Jørgensen, 1982; Jørgensen et al., 2000; Jørgensen and Svirezhev, 2004; Ulanowicz, 1997; Schneider and Kay, 1994; Odum, 1988, 1995; Bastianoni and Marchettini, 1997; Bendoricchio and Jørgensen, 1997; Wilhelm and Bruggenmann, 2000; Lin and Cao, 2006). The second law of thermodynamics states that entropy will spontaneously increase in an isolated system, but the applicability of the equilibrium assumption is challenged as ecosystems which are open systems, while they are far from equilibrium, and by the universe itself (Smolin, 1997).

Do ecosystems operate against the second law by becoming more ordered as they develop? Various hypotheses and theories on ecosystem development have been put forward to reconcile ecosystem behavior with the laws of thermodynamics. For example, Prigogine (1980) characterized ecosystems as “dissipative structures” which, despite minimizing locally entropy through the exchange of energy and material with their surroundings, contribute to universal increase in entropy. A common formulation of the proposed tentative fourth law of thermodynamics follows the maximum power principle: systems develop to maximize ‘eco-

exergy’ transformation (Jørgensen, 2002). Eco-exergy is the exergy (useable energy) embodied by an ecosystem and is a measure the distance from thermodynamic equilibrium (Jørgensen, 1982). It comes from relative gradient to the reference surroundings: potential exergy due to its position in a given body force field (gravitational, magnetic, etc.), kinetic exergy due to its velocity with respect to a fixed reference frame, physical exergy due to its pressure and temperature being different from the surroundings, and chemical exergy due to its chemical composition being different from the surroundings. Systems without exergy (i.e. those at equilibrium with their surroundings) are dead (Dewulf et al., 2008). Eco-exergy combines the physical, chemical and information exergy stored in biological systems, but its full quantification requires, e.g. information at the genetic level, the species level, and all pathways through which information or energy can flow. For these reasons, accounting for the exergy storage for entire ecosystems remains rather impractical (Jørgensen et al., 2007; Dewulf et al., 2008), but the problem can be simplified from the systems standpoint.

Schneider and Kay (1994) put forward the “maximum exergy dissipation theory”. They hypothesized that exergy dissipation is the goal of ecosystem development and concluded that the surface temperature was an integrated indicator to measure ecosystem organization; in colloquial terms a more efficient system should run cooler. The study of Luvall and Holbo (1989) provided evidence which supported this theory, and demonstrated using thermal imaging that more complex ecosystems had cooler radiometric

surface temperature. Recently, Aerts et al. (2004) used the thermal buffer capacity (TBC) as an indicator of ecosystem restoration. They suggested that TBC holds a strong signaling function capable of detecting initial rehabilitation failure and can be used to monitor ecosystem development. However such indicators may be impractical for ecosystem-level comparisons if the study ecosystems exist under conditions of differing incident solar radiation loads. Despite historical extensive investigations on ecosystem thermodynamics from the theoretical standpoint (e.g. Schneider and Kay, 1994) there exist no long-term studies of the thermal characteristics of ecosystem development despite heightened recent calls to quantify the biophysical consequences of land cover change on the climate system (Chapin et al., 2008; Jackson et al., 2008).

The largest difference between ecosystems and abiotic systems is self-organization. In the 1940s, self-organization was coined to label processes in which systems become more organized over time, without being ordered by outside agents or by external programs (Ashby, 1947). It is the spontaneous emergence of macroscopic order from microscopic disorder under conditions far from the thermodynamic equilibrium (Schrödinger, 1944; Müller and Fath, 1998). Bénard cell and B-Z reaction are classic simple self-organizing systems. Identical characters are found in these systems as well as ecosystem. They are: (1) Openness: input and output flow exchange through the boundary; (2) Input limitation: they need a certain level of input to maintain structure and function and if these limitations are not met, the system will crash; (3) Controlled by the trade-off between two opposite developing orientations. One is normal spontaneous process; the other is negative feedback process. The combination of positive and negative feedbacks shapes the structure of the system; (4) Adjusted by self-motivated and co-evolutionary negative feedback. Although the feedback is opposite to the normal spontaneous process, it is self-motivated. The self-organizing process can evolve with environment conditions.

Solar energy is the ultimate energy input for terrestrial ecosystems, and different ecosystems gain variable levels of energy even if they are bathed by the same amount of radiation, i.e. the net radiation may differ even if incident radiation is identical. The energy that is gained by an ecosystem determines the magnitude of exergy storage and dissipation, and the exergy state is regulated by negative feedbacks. For example, evaporation and metabolism act as negative feedbacks against the increase in ecosystem temperature heated by solar radiation by transferring radiation into latent heat and chemical exergy (the latter via photosynthetic products). Surface temperature thus integrates response of physical and physiological canopy behavior (Jones, 1999; Moran, 2000; Samson and Lemeur, 2000; Allen et al., 2001). From the physical aspect, according to the Stephan-Boltzmann law, energy flux density, $ULR = \varepsilon\delta T_c^4$, where ε is emissivity, δ is the Stefan-Boltzmann constant, and T_c is canopy temperature. Lower canopy temperatures induce lower longwave radiation loss (Kay et al., 2001). Incoming energy is primarily dissipated through evapotranspiration in ecosystems where water is available (Fig. 1) which cools leaf and canopy temperature (Gates, 1968). Schneider and Kay (1994), as stated, proposed that in the same environment, when ecosystems bathed by equal amount of radiation, the more developed or organized ecosystem attempts to capture more solar energy and dissipates this energy against a larger energy gradient. Thus more developed ecosystem should have the lowest canopy temperature.

In our study, we explore thermodynamic theory to (1) assess self-organization of vegetation and (2) to predict possible effects of land use change on local climate. The study ecosystems are located in the Xishuangbanna on the northern edge of tropical Southeast Asia, in an area encountering rapid conversion of primary forest to rubber plantations with concomitant invasion of exotic species. We explore thermodynamic characteristics of this complexity gradient.

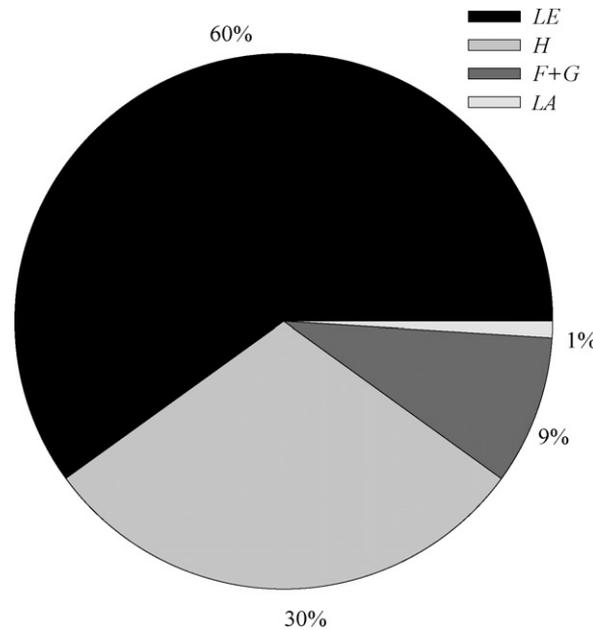


Fig. 1. Average energy balance for forest ecosystem. R_n : net radiation; LE: latent heat flux; H: sensible heat flux; G: soil heat flux; F: plant heat flux; LA: metabolism energy flux (He, 2000.).

2. Study sites and methods

2.1. Study sites

The study sites are located in Menlun, Xishuangbanna (21°54'N, 101°46'E, 580 m asl). Annual mean temperature is 21.8 °C and the average minimum annual temperature is 7.5 °C. Annual precipitation averages 1557 mm, of which ca. 85% occurs during the May–October rainy season. The November–April dry season comprises both a cool dry season from November to February and a hot dry season from March to April. The cool dry season is characterized by relatively low temperatures and heavy fog during the night through morning. The hot dry season is dry and hot during the afternoon and with fog in the morning only. The soil in the area below 1000 m elevation, where the study ecosystems are located, is laterite (Cao et al., 2006).

We selected 5 plant communities along a gradient of increasing human disturbance to represent a gradient of ecosystem self-organization. From least to most disturbed, this gradient includes a tropical seasonal rainforest, an artificial tropical rainforest, a rubber plantation, a 13-year-old *Chromolaena odorata* community and a 1-year-old *C. odorata* community. Tropical seasonal rainforests existed on all plots before human disturbance. The tropical seasonal rainforest (21°57' N, 101°12' E) is a permanent plot dedicated to long-term ecological research and managed by the Forest Ecosystem Research Station of Xishuangbanna Tropical Botanical Garden and is part of the ChinaFlux long-term monitoring project. The tropical seasonal rainforest is one of the most luxuriant primary forest types in Xishuangbanna, and is widely distributed in wet valleys, low hills and plains below 1000 m asl. Canopies are typically diverse in composition and structure, and comprised of three layers (Zhang and Cao, 1995; Cao and Zhang, 1997). The overstory can exceed 40 m in height, the upper-midstory is between 16 and 30 m and the lower-midstory is classified as those plants under 16 m. Shrubs and herbs in the understorey make the soil cover closed. Dominant species are *Pometia tomentosa*, *Barringtonia macrostachya* and *Gironniera subaequalis* (Cao et al., 1996).

The artificial tropical rainforest plot (21°55'N, 101°16'E) is dominated by rubber (planted in 1960), *Rauvolfia vomitoria* (planted in

Table 1
Plot information for the five study communities in Xishuangbanna, southwestern China.

	Tropical seasonal rainforest	Artificial tropical rainforest	Rubber plantation	<i>C. odorata</i> community (13 years)	<i>C. odorata</i> community (1 year)
Land use	Primary forest	Transitional forest	Plantation	Fallow	Fallow
canopy height (m)	35	20	17	2	2
Altitude (m)	756	560	570	585	580
Slope	Valley	Flat	Flat	Flat	Flat

1971), *Baccaurea ramiflora* (planted in 1979), *Calamus henryanus* and *Homalomena occulta* (planted in 1980). It is a compound artificial forest that is designed to simulate the composition and structure of a tropical rainforest. There are 16 species of liana and epiphytes and 67 species of grass in the understory. Except for rubber, all tree species are native species and familiar to local tropical seasonal rainforests (Tang et al., 2003).

The rubber plantation (21°54'N, 101°16'E) was established in 1984 in rows separated by 7–8 m with individual trees at 2–3 m spacing. To foster rubber production, fertilizers were applied to the plantation once or twice every year and understory species were weeded regularly.

C. odorata is a perennial herbaceous species that forms a dense, tangled canopy with an average height of 1.5–2.0 m. It occasionally reaches a maximum height of 5–6 m as a climber on other plants. *C. odorata* is native to America and is a widely distributed invasive across tropical Asia, western Africa, and in parts of Australia. The 13-year-old *C. odorata* community (21°55'N, 101°16'E) originated after a burn within the tropical botanical garden. The 1-year-old *C. odorata* community developed on a cleared plot which was intended for *Anthocephalus chinensis* establishment. Detailed plot information and locations are given in Table 1 and Fig. 2.

2.2. Methods

2.2.1. Species richness

The number of species in the tropical seasonal rainforest was summarized using data from the forest ecosystem research station (FERS) of Xishuangbanna Tropical Botanical Garden in 2007. The understory plants of the rubber plantation were eliminated to reduce competition for water and nutrients as stated, so only individuals with DBH > 2 cm were considered for species richness in the tropical rainforest and rubber plantation plots for the purposes of this analysis. To quantify species richness in the *C. odorata* commu-

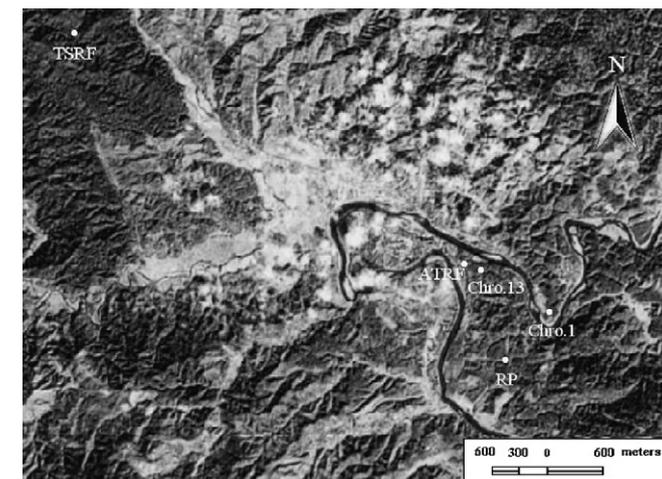


Fig. 2. A map of the study plots in Xishuangbanna, China. TSRF: tropical seasonal rainforest; ATRF: artificial tropical rainforest; RP: rubber plantation; Chro.13: 13-year-old *C. odorata* community; Chro.1: 1-year-old *C. odorata* community.

nities, we investigated all the species in the four corners and center of five 1 m × 1 m sub-plots.

2.2.2. Biomass and productivity

The biomass and productivity of the tropical seasonal rainforest plot, artificial tropical rainforest and rubber plantation have been reported by earlier studies (Zheng et al., 1998; Zheng et al., 1999; Jia, 2006; Tang et al., 2003). In September 1 (rainy season), 2007, all of the plants in four random chosen sub-plots (1 m × 1 m) in each *C. odorata* community were harvested and sorted to separate aboveground and belowground components. Harvested plants were oven-dried at 80 °C until the weight was constant. Dry biomass per hectare was then calculated. Because most of the aboveground parts of *C. odorata* community regenerates annually, productivity was estimated by the aboveground biomass. P/B is calculated by the ratio of production to biomass.

2.2.3. Indicators of ecosystem self-organization

Net radiation (R_n) is the net energy that is gained by ecosystems, and represents the balance between upward and downward shortwave and longwave radiation flux of the land surface:

$$R_n = DR - UR - (ULR - DLR) \quad (1)$$

where DR is downward shortwave radiation (solar radiation), UR is upward shortwave radiation (reflected radiation), DLR is downward longwave radiation and ULR is upward longwave radiation. A higher value of R_n/DR implies higher ecosystem energy capture.

Canopy TBC is an integrated indicator of a negative feedback that is a result of the regulation of incident radiation. Luvall and Holbo (1989) proposed the thermal response number (TRN) to quantify the buffer capacity of a system against incoming energy.

$$TRN = \frac{\sum_{t_1}^{t_2} R_n \Delta t}{\Delta T} \quad (2)$$

where $\sum_{t_1}^{t_2} R_n \Delta t$ is the net radiation R_n over the time interval Δt ; and ΔT is temperature variation over Δt , chosen here to be 1 day. TRN can be simply interpreted as the amount of radiation required to change one unit temperature as a logical metric for comparison of thermal properties across ecosystems. It is similar, conceptually, to the specific heat capacity as influenced by vegetation characteristics and minimized the impact of radiation environment. TRN is used in this study rather than surface temperature for a comparative analysis of ecosystems.

In summary, self-organization is measured through energy capture ability by R_n/DR and exergy dissipation ability by the TRN (Fig. 3). From the definitions above, a more self-organized system will have higher values of both R_n/DR and TRN than an ecosystem with relatively lower self-organization. All the indicators are ratios which can be used to assess and compare the study ecosystems, which have similar but not identical radiation environments as they are all located within a similar expanse.

Observation towers built in the tropical seasonal rainforest (70 m) and the artificial tropical rainforest (31 m) provided the access to the canopy. A vehicle with a 25 m aerial platform was used to reach the canopy of rubber plantation. A bamboo shelf

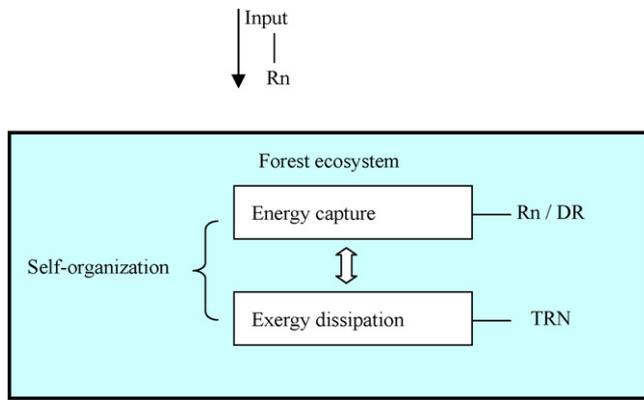


Fig. 3. Thermodynamic indicators of ecosystem self-organization. R_n/DR : the ratio of net radiation to downward short wave radiation (solar radiation); TRN: thermal response number.

(5 m) was placed in the *C. odorata* communities to mount equipment. Four automatic micrometeorological configurations were employed for simultaneous measurement. Kipp & Zonen CNR1 radiometers were used to measure DR (0.3–3 μm), UR (0.3–3 μm), DLR (5–42 μm) and ULR (5–42 μm), and were installed 3–5 m above the respective canopies. HMP45C T/RH analyzers (Vaisala Inc.) were used to measure air temperature and relative humidity at 1.5 m above each canopy. All micrometeorological data were automatically logged every 10 min. Tropical seasonal rainforest data was provided by the Chinaflux long-term observation project with identical radiometric and micrometeorological instrumentation. Experiments were carried out in October 3–6 and 13–16, 2007 (at the end of the rainy season), January 29–30 and February 2–4, 2008 (cool dry season) and March 21–25, 2008 (hot dry season). Canopy surface temperature was measured with thermal cameras (Flir P25, accuracy $\pm 2\%$, resolution 320×240 pixels) mounted 3–5 m above the canopies. Only two thermal cameras were available; these were rotated among sites. Final canopy temperatures were calculated using the relationship between canopy temperature and ULR ($R^2 > 0.96$). Emissivity of plant canopies is between 0.95 and 0.98 (Nichol, 1994; Brutsaert, 1982; Jones et al., 2002; Samson and Lemeur, 2000; Aerts et al., 2004); 0.95 was used here. To reduce stochasticity due to environmental conditions, average values of the same time on rain-free days were used to calculate R_n/DR and daily averaged TRN.

3. Results

3.1. Species richness

The tropical seasonal rainforest contains 311 woody species, the highest number of species among the investigated communities (Table 2). 67 species of trees and 29 species of shrubs are planted in artificial tropical rainforest (Tang et al., 2003). The rubber plantation is artificial vegetation, and only rubber trees are allowed to grow to maturity. *C. odorata* dominated in *C. odorata* communities. In the 13-year-old plot, procumbent *C. odorata* reached 5 m, *Pueraria stricta* Kurz was a canopy codominant and 6 other species comprised minor components of the canopy. 95%

Table 2
Species richness of the study plots.

	Tropical seasonal rainforest (DBH > 2 cm)	Artificial tropical rainforest (DBH > 2 cm)	Rubber plantation (DBH > 2 cm)	<i>C. odorata</i> community (13 years)	<i>C. odorata</i> community (1 year)
Richness	311	96	1	8	10

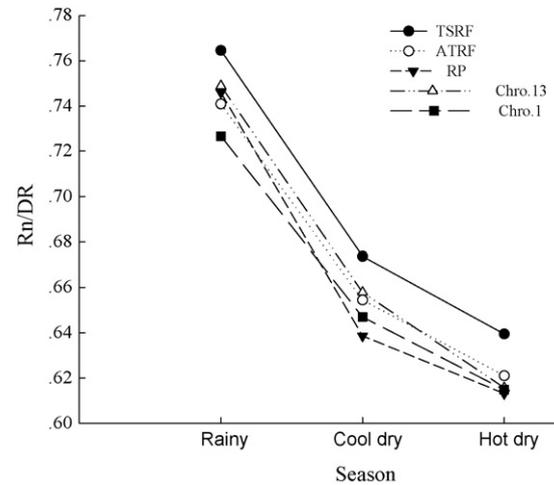


Fig. 4. Ratio of daily total net radiation to downward short wave radiation at the study plots during the three seasons.

of the canopy in the 1-year-old plot was covered by *C. odorata* and *Pleioblastus amarus* (Keng) Keng. f. comprised 60% of the understory (Table 2).

3.2. Biomass and productivity

The artificial tropical rainforest accumulated more biomass than the tropical seasonal rainforest, which in turn accumulated more biomass than the rubber plantation. 97.7% of the total biomass was distributed in the tree layers in the tropical seasonal rainforest, which is higher than artificial tropical rainforest (92.8%). The 13-year-old *C. odorata* community accumulated higher biomass than the 1-year-old community, and *C. odorata* comprised 91.1% of the biomass. *C. odorata* accounted for 76.9% of the total biomass in the 1-year-old *C. odorata* community (Table 3).

The rubber plantation has the highest ratio of production to biomass among the forested ecosystems, meaning that the residence time of biomass in the ecosystem was shortest. However, the turnover rates of the forested ecosystems are all slower than the *C. odorata* communities (Table 3).

3.3. Energy capture ability

Energy capture, as quantified by the R_n/DR , was observed to decrease from the rainy season to the cool dry season and reaches the lowest point in hot dry season, on average (Fig. 4). Energy capture ability was highest in the tropical rainforest on an annual basis, and was notably low in other communities during the hot dry season. The rubber plantation has the poorest energy capture ability in both the cool and hot dry seasons (Fig. 4).

3.4. Exergy dissipation ability

TRN and R_n/DR showed similar trends and decreased from the rainy season to the dry seasons. There was a large TRN gap between the tropical seasonal rainforest and other communities in the hot dry season. In the cool dry season, the ecosystems fell into three TRN groups: (1) tropical seasonal rainforest, (2) artificial tropical rain-

Table 3
Biomass and production of the study communities.

	Tropical seasonal rainforest			Artificial tropical rainforest			Rubber plantation		C. odorata community (13 years)		C. odorata community (1 year)		
	Tree layer	Shrub layer	Herb layer	Tree layer	Shrub layer	Herb layer	Liana	Above ground	Under ground ^a	Above ground	Under ground	Above ground	Under ground
Biomass ($t\text{ hm}^{-2}$)	352.5	4.7	0.5	362.5	19.3	5.0	3.6	108.4	19.5	14.5	4.5	9.5	6.1
Production ($t\text{ hm}^{-2}\text{ a}^{-1}$)	25.8			22.3				16.1		14.5		9.5	
P/B	0.07			0.06				0.13		0.76		0.61	

^a Due to the dominant tree species is rubber in artificial tropical rainforest, the under ground biomass of rubber plantation was estimated by the ratio of above ground biomass to under ground biomass in tree layer in artificial tropical rainforest.

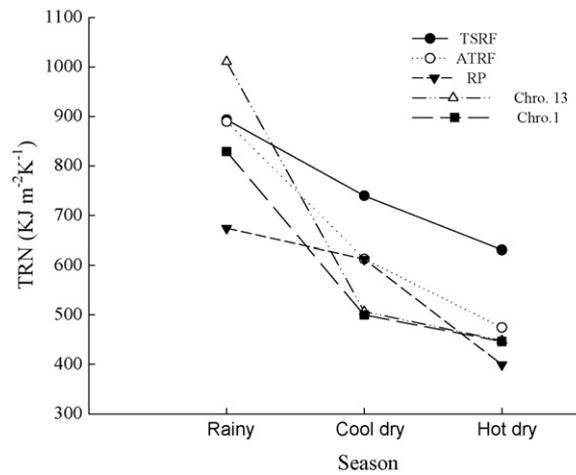


Fig. 5. The thermal response number (TRN) of the study plots separated by season.

forest and rubber plantation, (3) *C. odorata* communities. Although TRNs of *C. odorata* communities were very low in dry season, they increased sharply in rainy season, when the TRN of the 13-year-old *C. odorata* community even exceeded that of the tropical seasonal rainforest (Fig. 5).

3.5. Self-organization

All the communities were most self-organized, based on the exergy dissipation criterion for self-organization, during the rainy season. From the thermodynamic viewpoint, this energy gain is used to build and maintain self-organizing structures. Self-organization increased more rapidly in the *C. odorata* communities than the forested ecosystems from the cool dry season to the rainy season. Although the rubber plantation obtained more energy in rainy season than other seasons, it used less energy to increase exergy dissipation in comparison with other communities. The tropical seasonal rainforest was more self-organized than other communities during the dry season as evidenced by the relatively high R_n/DR and TRN values (Fig. 6).

3.6. Land use change on local temperature

The daily air temperature range above the rubber canopy was the largest in the hot dry season and the rainy season. The highest (lowest) above-canopy air temperatures are 4 °C (1 °C) higher

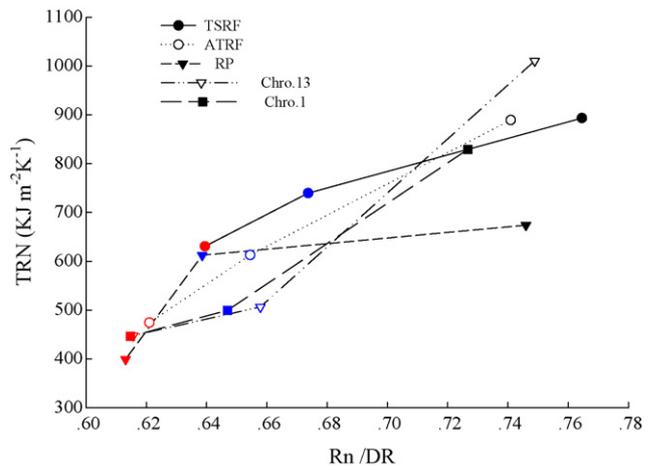


Fig. 6. Self-organization of the communities as quantified by both the net to downward shortwave radiation ratio (R_n/DR) and the thermal response number (TRN). Red: hot dry season; Blue: cool dry season; Black: rainy season.

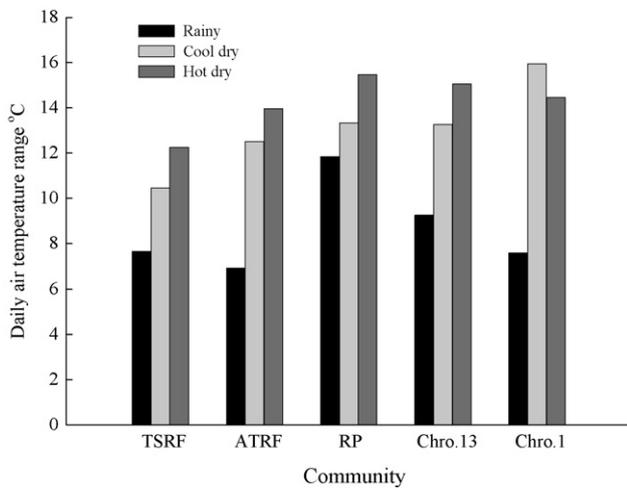


Fig. 7. Daily air temperature range across the three seasons for the study plots. Abbreviations: follow Fig. 2.

Table 4

The daily canopy temperature range and the annual average variance after TSRF is transferred to ATRF, RP, Chro. 13, Chro. 1.

	Cool dry season TSRF °C	Hot dry season TSRF °C	Rainy season TSRF °C	Annual variance
TSRF	11.85	14.01	9.12	
ATRF	13.91	18.60	8.95	2.16
RP	13.59	21.47	12.09	4.05
Chro.13	16.93	18.90	8.19	3.01
Chro.1	16.87	19.02	10.08	3.66

Assuming that DR remains unchanged, while UR/DR, R_n /DR and TRN change with land use change. Abbreviations: follow Fig. 2.

(lower) than the air temperature above the tropical seasonal rainforest during the hot dry season (Fig. 7). After TSRF is transferred to other vegetation types, the daily canopy temperature range will be changed based on the results of this study; averaged across the annual cycle the difference in the daily temperature range from various land use conversions would follow the sequence of TSRF-RP > TSRF-Chro.1 > TSRF-Chro.13 > TSRF-ATRF. Based on results from this study, a land use conversion from TSRF to rubber plantation may increase the daily canopy temperature range in the hot dry season by 7.4 °C. A land use conversion from tropical seasonal rainforest to *C. odorata* will have the largest impact on daily canopy temperature range in cool dry season (Table 4).

4. Discussion

According to the maximum dissipation theory, if an ecological community is more developed and self-organized, it would both gain more energy and dissipate this energy more efficiently (Schneider and Kay, 1994), increasing both in the R_n /DR and TRN and tend toward the upper-right hand section of Fig. 6. The distance between points in Fig. 6 can be taken to represent the difference of self-organization based on this criterion. Observations revealed that the tropical seasonal rainforest retained the highest heat capacity and showed the strongest self-organization during the hot dry season among the studied communities. The lowest temperature at night is under 15 °C during the middle of December to the end of March which cannot meet the requirement of rubber growth temperature 18 °C (Shen, 1991). Relative humidity decreases from the cool dry to the hot dry season, and as a result rubber takes the deciduous strategy in Xishuangbanna. With the defoliation of rubber and wither of *C. odorata*, these communities became very 'leaky' in terms of their energy capture, and self-organization decreased

to a very low level during the dry season (Fig. 6). However, the tropical seasonal rainforest has a low turn-over rate (Table 3) and its structure is complex: the well developed understory plants play an important role in soil protection and water conservation; three layers of trees and high biodiversity ensures canopy closure which maximizes radiation capture, and optimizes exergy dissipation across seasons compared to the other ecosystems as evidenced by Fig. 6. The leaf area index (LAI) of the tropical seasonal rainforest in March 2008 was 4.75, which was much higher than 1.46 for the rubber plantation and 3 for the artificial tropical rainforest (data from FERS). The tropical seasonal rainforest is a well developed energy degrader, pumping entropy out of the ecosystem to maintain organization and playing important role in temperature stabilization through this negative feedback function, especially during the dry season (Table 4, Fig. 7).

During the rainy season, leaves flourish, and plants capture more energy to photosynthesize and transpire. Evapotranspiration is the primary pathway for plants to dissipate exergy. The measured maximum transpiration rate is 15 mmol m⁻² s⁻¹ for *C. odorata*, 5.85 mmol m⁻² s⁻¹ for *Pometia tomentosa* (the dominant species in the tropical seasonal rainforest), and 2.97 mmol m⁻² s⁻¹ for rubber (FERS, unpublished data). *C. odorata* can thereby adjust the canopy surface temperature more effectively by adjusting evapotranspiration across a wider range. Both leaf development and evapotranspiration abet exergy dissipation. *C. odorata* expands rapidly at the onset of the rainy season. Its high transpiration rate dissipated absorbed radiation into latent heat (at low level of exergy), and the strong self-organization of *C. odorata* community under favorable conditions as demonstrated by its efficient energy utilization may help explain its successful invasion.

Canopy temperature has a great influence on micrometeorology. The study of climate over the past 40 years showed a significant air temperature increase in Menglun, Xishuangbanna, especially during the dry season (Li, 2001). Synchronously, from 1988 to 2003, rubber plantations expanded at an average rate of 604.12 hm⁻² a⁻¹, and natural forests disappeared at an average rate of 431.17 hm⁻² a⁻¹ (Liu et al., 2005). Our study corroborates the relationship between overspreading of rubber plantation and local warming (Table 4, Fig. 7). To mitigate the warming trend, developing compound and multi-layer plantation may be a good choice.

There are many elements affecting ecosystem self-organization, for instance, the ecosystem structure, species composition, the albedo of the canopy, and environmental factors. It is argued here that the holistic viewpoint of ecosystems via thermodynamic principles can be an effective way to quantify community ecophysiology via the thermal regulation of plant canopies. Ecosystems are complex systems that are not completely "reducible" to their components, and thus the integration rigorous, reductionistic understanding of the mechanisms of ecosystem behavior should be combined with a comprehensive view of ecosystem function through a holistic viewpoint. The indicators measured in this research reflected the integrated thermal properties of plant communities and their sensitivity to seasonality. The expected ecosystem level thermal attributes were revealed by the combination of theory that would expect a tropical rainforest to have greater energy capture and exergy dissipation characteristics, and environmental measurements that demonstrated that it does.

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