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Short communication

The effect of drought stress on self-organisation in a seasonal tropical rainforest

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ABSTRACT

From late 2009 to 2010, southwestern China experienced a severe drought. We evaluated the self-organisation of a seasonal tropical rainforest in response to drought stress. The forest had the least self-organization in 2010, and during the dry season (March–April) of 2010, the forest was least able to capture exergy (Rn/DR). The rate of long wave radiation (I/DR) loss was highest in 2010. The thermal response number of canopy temperature (TRNc) and Rn/DR showed similar trends and decreased from the rainy season to the dry seasons in each of the three years.

1. Introduction

Relatively small changes in tropical rainforest dynamics have the potential to substantially affect canopy structure and gross ecosystem productivity and thus feedback to climate change. Forests respond to a variety of interannual environmental changes, particularly drought events. For instance, Amazon forests appear vulnerable to increasing moisture stress, with the potential for large carbon losses to exert feedback on climate change (Asner et al., 2004; Asner and Alencar, 2010; Malhi et al., 2008; Phillips et al., 2009; Anderson et al., 2010).

In recent years, many ecophysiological studies of drought tolerance or adaptation potential in climate change scenarios have been published (Asner et al., 2004; Meir et al., 2006; Misson et al., 2010). However, the majority of these studies focus on carbon, whereas comparative studies in mixed forests are rare. Furthermore, increased moisture stress is a dominant feature of some modelled climate scenarios for tropical rainforest (Cox et al., 2008; Salazar et al., 2007).

Over the long term, the incoming solar radiation (short-wave radiation) absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing long-wave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This exergy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by long-wave radiation that is absorbed by clouds and greenhouse gases (Wagendorp et al., 2001). The atmosphere in turn radiates long-wave exergy back to Earth as well as out to space. Albedo is one key variable controlling the radiation exergy budget of the land surface. The albedo determines how much solar radiation (short-wave radiation) is absorbed at the surface (and is thus available for biophysical processes) and how much is reflected back into the atmosphere. High temperature indicates high long-wave emission (Allen et al., 2001). 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. From the physical aspect, according to the Stephan–Boltzmann law, exergy flux density, $ULR = \varepsilon\delta Tc^4$, where ε is emissivity, δ is the Stefan–Boltzman constant, and Tc, is canopy temperature. Higher canopy temperature indicates higher long-wave radiation loss (Schneider and Kay,

Abbreviations: Rn/DR, capture exergy; I/DR, the rate of long wave radiation; TRNc, the thermal response number of canopy temperature; *Tc*, canopy temperature; Ws, wind speed; VPD, vapour pressure deficit; LAI, leaf area index; ET, evapotranspiration.

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1994). In a tropical rainforest with close canopy, the exergy balance could approximate: Net radiation (Rn) is nearly equal to latent heat flux (LE) plus sensible heat flux (Hs). Ecosystem is intrinsically distinguished from abiotic systems by its self-organization ability. Therefore, assessing the ecosystem self-organization ability is one of the key scientific issues to understand the process. The hypotheses of exergy transformation in self-organizing open systems, quite beyond classical energetics, involve concepts of self-development in exergy terms. During self-organization, system designs develop and prevail that maximise power intake, exergy transformation, and those uses that reinforce production and efficiency (Odum, 1988). Lin et al. (2009) developed thermodynamic indicators of exergy capture and dissipation to quantify the degree of a forest's self-organisation. These indicators of the ecosystem's operational self-organisation are particularly useful for studies of complex terrestrial ecosystems. Over three years (2004–2006), they found that the average self-organisation values were clearly separated by season. Reflection and long wave radiation are the two primary pathways for exergy loss. In the tropical seasonal rainforest they studied, long wave radiation contributed most to exergy loss and was negatively correlated with the ability to capture exergy (Rn/DR). From late 2009 through 2010, the Xishuangbanna region in southwestern China experienced the most severe drought on record since 1959, providing a unique opportunity to directly evaluate how these self-organisation indicators change with drought stress in a tropical rainforest. In this study, we will explore thermodynamic theory to assess the effect of drought stress on self-organisation in a seasonal tropical rainforest.

2. Methods

2.1. Study site

The study was conducted at a tropical seasonal rainforest site (21°57′ N, 101°12′, 750 m asl) in the town of Menglun, Xishuangbanna Prefecture, southwestern China. The permanent ecological research plot is in the centre of the Nature Reserve; it shows no sign of recent anthropogenic disturbance other than hunting trails. The annual mean temperature is 21.8 °C, and the average minimum annual temperature is 7.5 °C. The mean annual wind speed is 0.5 m s^{-1}. Annual precipitation averages 1557 mm, of which 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 characterised by relatively low temperatures and heavy fog during the night and throughout the morning. The hot dry season is dry and hot during the afternoon, with fog occurring in the morning only. This site is located on a small flat area between two hills extending from east to west and is a permanent plot (dominated by *Paulownia Pometia tomentosa and Terminalia myriocarpa*) dedicated to long-term ecological research and managed by the Tropical Rainforest Ecosystem Station, the Chinese Academy of Sciences. The plot is also part of the ChinaFLUX long-term ecological monitoring project. This type of forest is primarily formed in wet valleys and lowlands and on low hills where heavy radiation fog frequently occurs (Cao et al., 1996).

2.2. Instruments and measurements

All measurements were made on a 72 m meteorological tower. Air temperature and humidity (HMP45, Vaisala, Finland), rainfall (52203, Young, USA), and global and infrared incident and reflected radiations (CNR1, Kipp and Zonen, USA) were measured above the canopy. All meteorological data were collected at 1 min intervals and compiled as 30 min averages or sums with a CR1000 datalogger (Campbell Scientific Inc., USA). The vapour pressure deficit (VPD) was calculated based on air temperature and humidity.

Canopy temperature (*Tc*) was measured with an infrared thermometer (Apogee, USA) mounted 52 m above the ground.

The leaf area index was measured with a LAI-2000 (LI-COR Inc., USA) every month.

2.3. Data analysis

Mathematic analysis of the thermodynamic parameters describing exergy capture ability and exergy dissipation ability of ecosystem was carried out in terms of exergy balance, thermodynamics, physiology and ecology. It is suggested that Rn/DR (net radiation/downward short-wave radiation) (Schneider and Kay, 1994) can be used to describe exergy capture ability, and TRN (thermal response number) can be used for the measurement of exergy dissipation ability in this research.

Luvall and Holbo (1989) proposed the thermal response number (TRNc) to quantify the buffer capacity of a system against incoming exergy.

TRNc 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.

TRNc was calculated as $\sum_{t1}^{t2}\mathrm{Rn}(\Delta t)/\Delta T$, where $\sum_{t1}^{t2}\mathrm{Rn}(\Delta t)$ is the net radiation, Rn, over the time interval Δt, and ΔT is temperature variation over Δt, chosen here to be 1 day.

In summary, self-organization is measured through exergy capture ability by Rn/DR and exergy dissipation ability by the TRNc.

VPD was calculated from hourly measurements of air temperature and relative humidity.

3. Results

3.1. Climate factors patterns

The meteorological measurements showed seasonality in rainfall, air temperature (Ta), wind speed (Ws), vapour pressure deficit (VPD) and leaf area index (LAI). In this study site, the drought lasted from the beginning of August 2009 until October 2010. The average rainy season (May–August) rainfall was only 57.4 mm in 2010, which is much lower than the average value for the past 50 years of 213.7 mm (Fig. 1). LAI was lower in 2010 than in 2008 and 2009 (Fig. 2d). LAI slowly decreased from the beginning of the dry season and in March 2010 was only 3.3 (SE = 0.39).

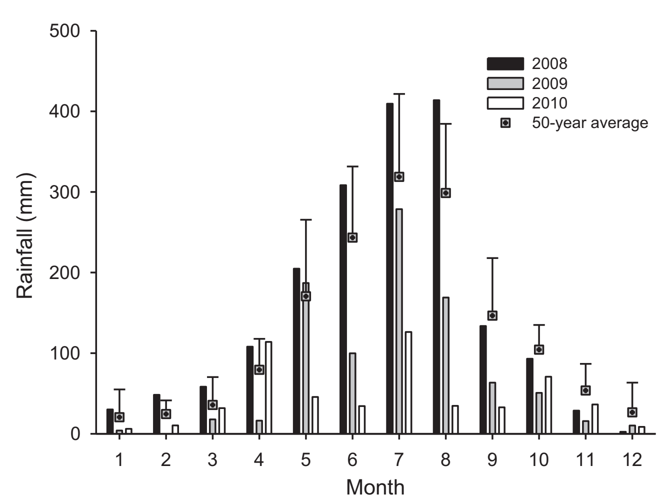

Fig. 1. Average monthly rainfall in the years 2008, 2009 and 2010, and for the past 50 years (+1 SE).

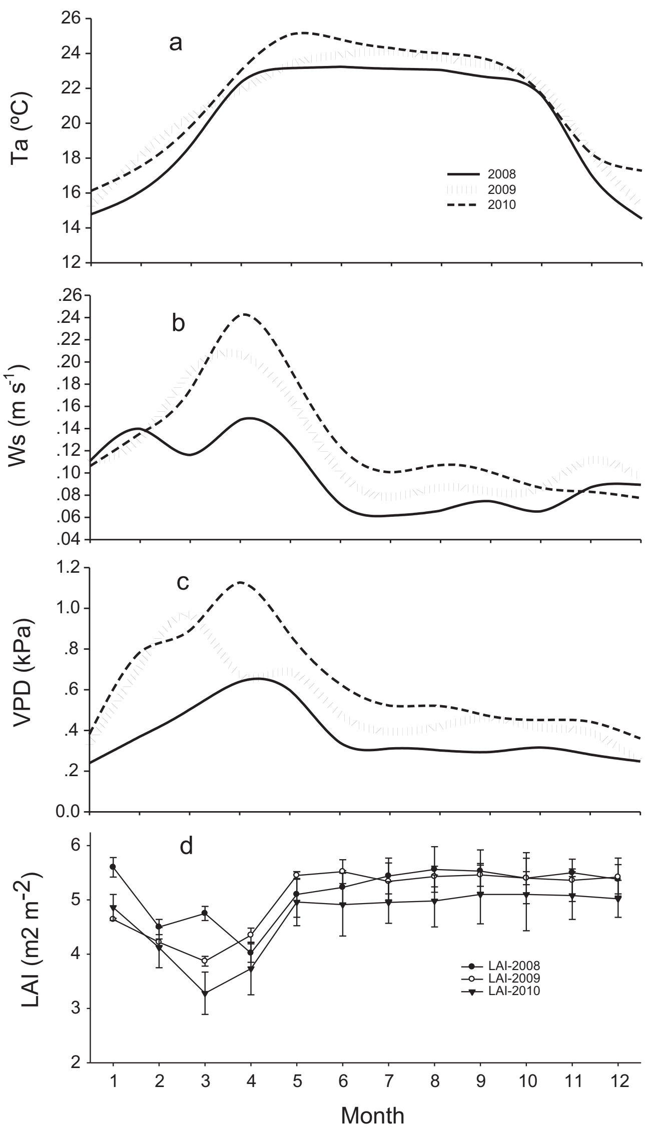

Fig. 2. Average annual fluctuations of environmental factors and LAI.

Ta in 2009 and 2010 were higher than in 2008, particularly in the dry season (March–April). Ws and VPD had similar patterns in the three years (Fig. 2b and c).

3.2. Self-organisation patterns

There was an obvious pattern in self-organisation over the three years. Self-organisation in 2010 was concentrated in the left bottom, and those in 2008 occupied the middle (Fig. 3).

3.3. Exergy capture ability

The lowest value for ability to capture exergy (Rn/DR) occurred during the dry season (March–April) in 2010 (Fig. 4a). The Rn decreased over the same period, resulting in the lowest ability to capture exergy in 2010 (Fig. 4a).

3.4. Exergy dissipation ability

TRNc and Rn/DR showed similar trends and decreased from the rainy season to the dry season in each of the three years. The dry season (March–April) of 2010 had the lowest values (Fig. 4b).

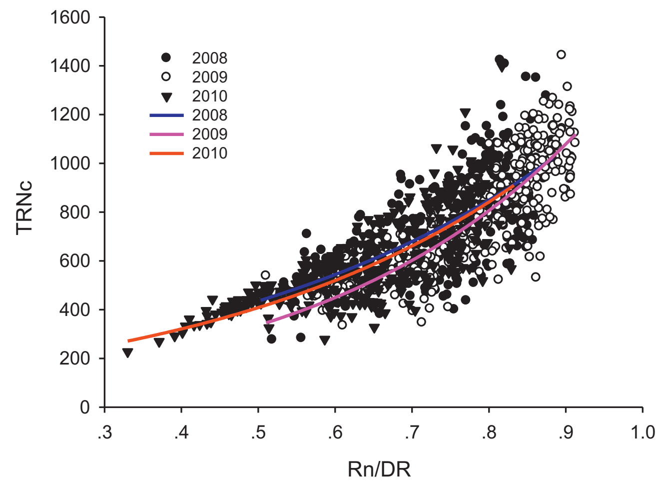

Fig. 3. Average annual patterns of self-organization.

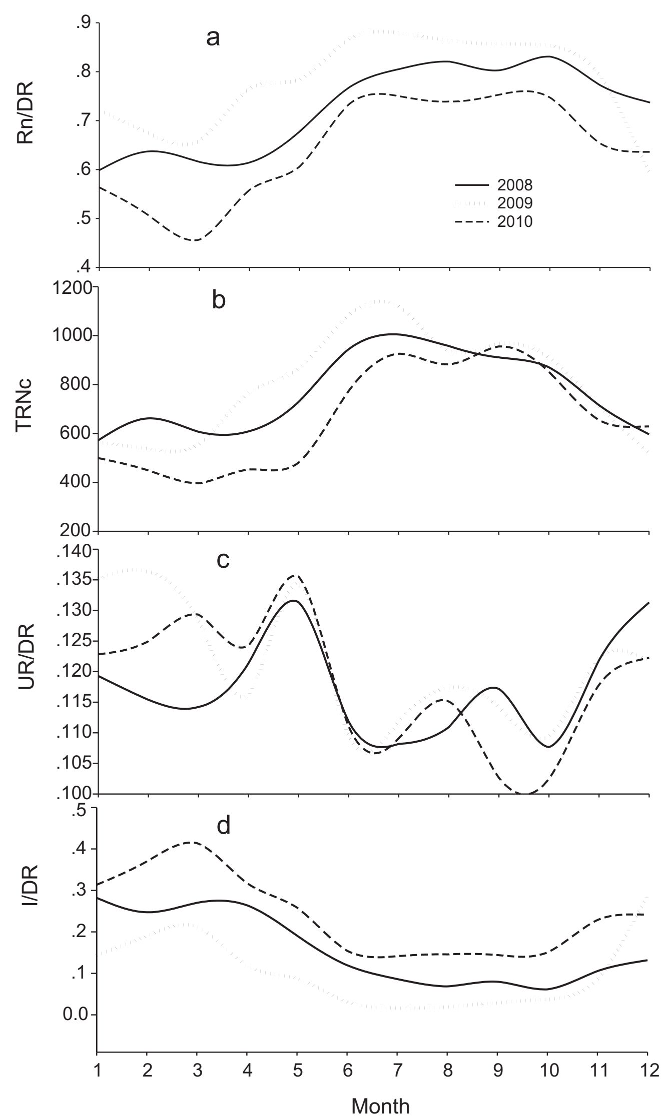

Fig. 4. Average annual fluctuations of net radiation/global radiation (Rn/DR), TRNc reflective radiation/global radiation (UR/DR) and net long wave radiation/global radiation (I/DR).

There were no significant differences in UR/DR among the three years (Fig. 4c).

Long wave radiation (I/DR) loss rates in 2010 were higher than they were in 2008 and 2009 (Fig. 4d).

4. Discussion

Self-organisation values in 2009 were located on the top of the regression line (Fig. 3), indicating that the forest was highly self-organised. However, self-organization in 2010 concentrated in the left bottom (Fig. 3), so the ecological community is less developed. It would both gain less energy and dissipate this energy less efficiently, decreasing both in the Rn/DR and TRN in the drought year.

The net radiation is energy that is available for evapotranspiration (ET), sensible heat convection and photosynthesis. Evapotranspiration is the primary way that a forest dissipates exergy. The annual total for ET in 2010 was only 780 mm, which is significantly lower than it was in 2008 (1038 mm) (unpublished data). In the dry year, the downward component of long-wave radiation is decreased and the upward component is increased (the canopy is warmer because of increased solar insolation and reduced evaporation due to soil moisture limitation). The severe drought not only decreased ET, but also may trigger additional ecosystem disturbances, releasing carbon to the atmosphere (Keitha et al., 2012). During drought the water potential and net photosynthesis (Pn) substantially decrease (Molnár et al., 2004). The reduction of Pn partially results from the closure of stomata due to water deficit, since decrease of stomatal conductance is the most efficient way to reduce water loss. In the tropical seasonal rainforest, presence or absence of leaves will not only affect surface energy partitioning but also the aerodynamic resistance of the surface.

VPD is correlated with soil moisture status through surface evaporation and planetary boundary layer feedbacks (Keitha et al., 2012). The high peak in VPD in the dry-hot season of 2010 in our study site indicates conditions of low soil moisture availability and high evaporative demand, which may be expected to result in low leaf conductance.

Prolonged droughts cankill trees (Allen et al., 2010). In the other hand, tree mortality may be cause forest structural and compositional change. Ecosystem self-organization are sensitive to plant community type, so the tropical rainforest may be lowly self-organized in the future. In the future, we would to quantify feedback of dynamic of rainforest to drought frequency, severity and duration.

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