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The effect of snow damage on self-organization in a primary subtropical evergreen broadleaved forest in Southwest China

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ABSTRACT

At the beginning of 2015, a primary subtropical evergreen broadleaved forest in Southwest China experienced an extreme snow anomaly. We used a thermodynamic approach to evaluate the self-organization of the forest in response to snow disturbance. We found that the snow disturbance induced severe vegetation damage, as indicated by LAI significantly decreased by 33.19% and 40.85% in 2015 than the pre-disturbance years (2013–2014), respectively. The forest had the higher self-organization in 2015 with the higher ability of capture exergy (Rn/DR) and dissipation exergy (TRNc). The changes in vegetation patterns of the primary subtropical evergreen forest enhanced the ecosystem self-organization. Our finding was inconsistent with the general theory that the disturbance of natural systems reduces exergy capture ability and increases exergy dissipation.

1. Introduction

Self-organization is a spontaneous process that can form a well-organized structure from random initial conditions. It is often used to reveal the stability and elasticity of a system (Ashby, 1945; Chen et al., 2018; Fotakis, 2015; Heylighen, 2008; Lin et al., 2011; Rocha, 1998). Thermodynamic approach is an important tool to study the self-organization pattern for various fields in physics, chemistry and those including in biological system (Lin et al., 2009; Rossi and Liveri, 2009; Sprott et al., 2002; Zehe et al., 2013). Ecosystem is a complex and open system characterized by a set of self-controlled structures, functions and pathways (Lu et al., 2011). The ecosystems couldn't only maintain their structure and development by absorbing external exergy, but also develop new structures and functions with the change of the environment (Lin et al., 2009). Therefore, ecosystems are complex self-organizing systems and can be thought of as thermodynamic systems, open to energy and matter (Coscieme et al., 2013). Energy (the capacity of a system to perform work) is the basic fundamental driving force for all biological and environmental processes, which depend on the transformation of energy potential and exist the general principles of thermodynamics in the structural and functional development of ecosystem (Kelso and Odum, 1972; Lu et al., 2015; Wang et al., 2021). As for as ecosystem research is concern, Lin et al. (2009) introduced a thermodynamic approach using indicators of exergy (amount of work) capture and dissipation to monitor the tropical plants species and rainforest ecosystem self-organization, what they defined as the comprehensive embodiment of exergy capture ability and negative feedback intensity. This approach is not only suitable for analyzing long-term changes in ecosystem changes, but also for real-time monitoring of forest health. In complex terrestrial ecosystems, using these indicators to study the self-organization are particularly useful (Lin et al., 2011), the average self-organization values are clearly distinct by season in the tropical rainforest. Song et al. (2013) evaluated the self-organization of the tropical rainforest in response to drought stress using the thermodynamic indicators in the same site. They found that the forest had the least self-organization during the dry season of dry year, the forest has

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least capable to capture exergy (Rn/DR).

Extreme climates such as heatwaves, droughts, storms, fires and extreme snow events have the potential to substantially affect canopy structure and lead to a decrease in forest ecosystem carbon stocks and associated exergy fluxes, which have the potential to negate an expected increase in terrestrial carbon uptake (Reichstein et al., 2013). Hence, forest ecosystems could be the most sensitive biome to climate extremes (Anderegg et al., 2012; Malhi et al., 2008; Phillips et al., 2009). Values of ecosystems and potential losses associated with their degradation are complex. Different evaluation approaches, such as carbon loss amount, plant mortality and top soil erosion, can estimate the absolute or relative magnitude of ecosystem damage caused by climate extremes (Anderegg et al., 2012; Lindroth et al., 2009; Muhr et al., 2009; Nepstad et al., 2007; Reichstein et al., 2013).

In recent years, several studies on extreme snow events have been explored in subtropical forests (Chen et al., 2021; Ge et al., 2015; Hao et al., 2011; Song et al., 2017a). In these connections, the extreme snow events frequency will be increasing in subtropical region, especially high-altitude locations (IPCC, 2021; O'Gorman, 2014). Although several studies have investigated the effect of climate change on the carbon balance, little is known about the effects of extremes snow on the self-organization of the primary subtropical forest, which will providing a unique opportunity to evaluate how the ecosystem self-organization change with the snow damage directly under the condition of climate change. In order to understand it further, we analysed three years of continuous measurements of exergy exchange across the biosphere/atm interface collected in the subtropical evergreen forest by means of the micrometeorology (eddy covariance) technique. The key objective of the present study was to quantify how exposure to snow damage affects ecosystem self-organization.

2. Materials and methods

2.1. Study site

The study was conducted in a subtropical evergreen broadleaved forest site (24°32′N, 101°01′E, 2476 m asl) in the town of Jingdong, southwestern China (Fig. 1). The annual mean temperature is 11 °C. Annual precipitation averages 1931 mm, of which 85% occurs during the rainy season (May–October). The forest is primarily dominated by *Lithocarpus hancei, Machilus gamblei, Castanopsis wattii*, and *Lithocarpus xylocarpus* (You, 1983). The mean canopy height is 20 m. The soil is loamy Alfisols, and the 3–7 cm organic carbon horizon has a pH of 4.5 (Chan et al., 2006; Liu et al., 2002). In this study site, the snow lasted from the beginning of 8 January 2015 until 11 January 2015 (Fig. S1). The snow event in 2015 was the strongest one since 1987 records began in this station, with heavy snow up to 50 cm depth and damage the forest

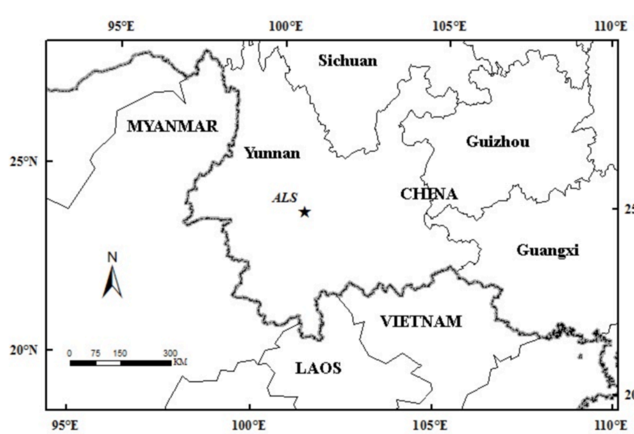

Fig. 1. The location of the study site (ALS: Ailaoshan).

severely, resulting in the broken of branches in the big trees (Fig. S2). We analyzed the data of a 3-year period between 1th January 2013 and 31th December 2015. The plot is also a part of the ChinaFLUX long-term ecological monitoring project. The permanent ecological research plot is in the centre of the Nature Reserve, and it shows no sign of recent anthropogenic disturbance other than hunting trails.

2.2. Instruments and measurements

All measurements were made on a 34 m meteorological tower. An instrument for measuring wind direction (W200P, Vector Instruments, Denhighshire, UK) was installed at the top of the tower. Radiation sensors for downward and upward, short-wave and long-wave radiation (CNR-1/CM11, Kipp & Zonen, Delft, the Netherlands) were installed at a 26 m height on a horizontal pole 3 m away from the tower. Instruments for measuring air temperature and air humidity (HMP45C, Vaisala, Helsinki, Finland) and wind speed (A100R, Vector Instruments, Denhighshire, UK) were installed at seven heights. Canopy temperature (Tc) was measured with an infrared thermometer (Apogee, USA) mounted 27 m above the ground. All the data were recorded at 30 min intervals and were collected by the data loggers (CR1000 and CR3000, Campbell Scientific, Logan, UT, USA). The leaf area index (LAI) was measured with a LAI-2200 (LI-COR Inc. USA) every month.

2.3. Data analysis

We used two indicators to evaluate the self-organization of the subtropical evergreen forest in response to snow damage. One is the exergy capture ability by Rn/DR (net radiation/downward short-wave radiation), and the other is the exergy dissipation ability by the TRNc (thermal response number of canopy temperature). TRNc was calculated as $\sum_{t1}^{t2} Rn(\Delta t)/\Delta T$, where $\sum_{t1}^{t2} Rn(\Delta t)$ is the net radiation, Rn, over the time interval Δt, and ΔT is temperature variation over Δt, chosen here to be 1 daily summed value from 30 min recorded data. VPD was calculated from hourly measurements of air temperature and relative humidity. The nonlinear regression was conducted to obtain the average annual patterns of self-organization (Sigmaplot 13.0, Systat Software Inc., CA, USA). To test the differences of these dependent parameters among these three years, one way analysis of variance (ANOVA) was performed using SPSS 26.0. (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Climate factors and LAI patterns

The meteorological measurements showed seasonality in net radiation (Rn), direct shortwave radiation (DR), air temperature (Ta), wind speed (Ws), and vapour pressure deficit (VPD) (Fig. 2). Rn and DR was higher in later dry season than that in rainy season in the three years (Fig. 2a, b). Ta was higher in the rainy season than in the dry season (Fig. 2c). Ws in 2015 remained a stable level in the whole year (Fig. 2d). The low value in VPD in late dry season of 2015 indicates conditions of high soil moisture availability due to the melting snow and low evaporative demand.

After the snow damage, LAI decreased by 33.19% and 40.85% in 2015 ($P < 0.001$) compared with pre-disturbance years (2013–2014), respectively (Fig. 3). It showed sharp increases (113%) from August of 2015 (Fig. 3), but remained significantly lower than the level before the snow damage (the average LAI of pre-disturbance years , $P < 0.001$).

3.2. Self-organization patterns

According to the Rn/DR and TRNc, we assessed the self-organization patterns of this forest. In 2013–2015, the relationship between Rn/DR and TRNc were exponential ($R^2 = 0.557$, $P < 0.001$; $R^2 = 0.415$, $P < 0.001$; $R^2 = 0.376$, $P < 0.001$, respectively), indicating that the rate of

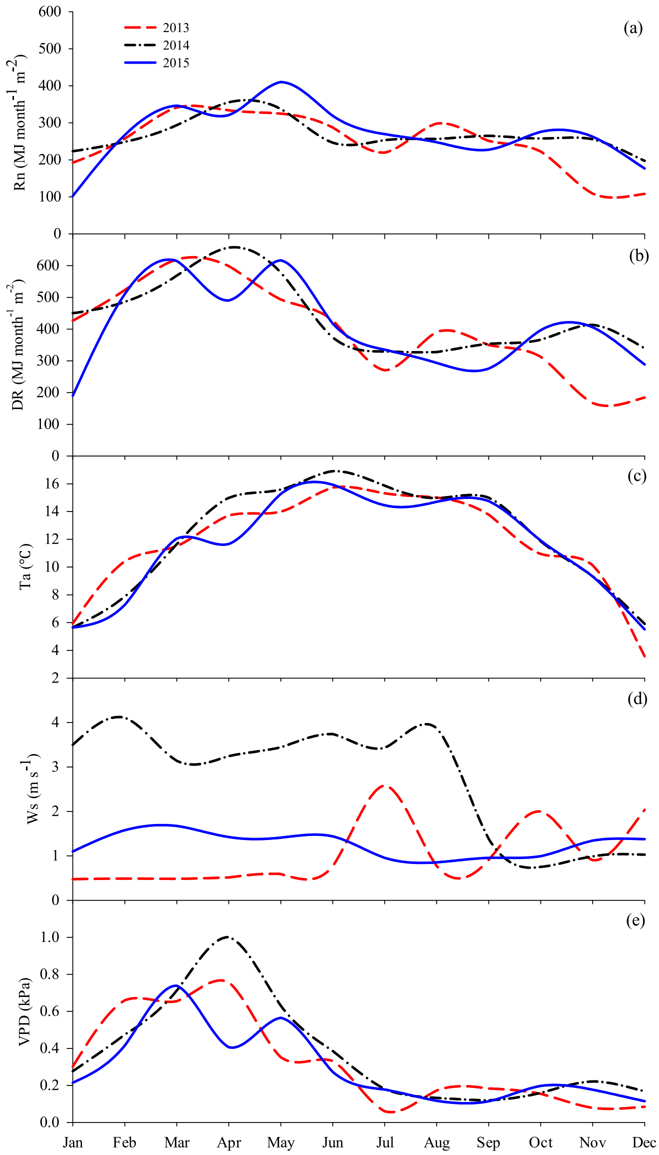

Fig. 2. Average annual fluctuations of environmental factors. (a) Net radiation (Rn), (b) Direct shortwave radiation (DR), (c) Air temperature (Ta), (d) Wind speed (Ws), and (e) vapor pressure deficit (VPD).

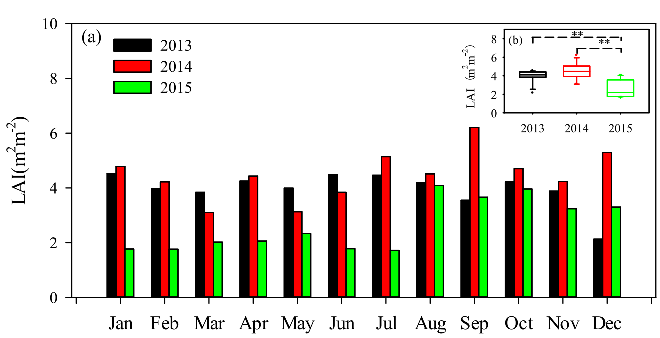

Fig. 3. Average monthly variations of leaf area index (LAI) from 2013 to 2015 (a), average yearly LAI patterns in boxplots (b), ** indicated the statistical differences ($P < 0.001$).

exergy dissipation increased exponentially with the exergy capture (Fig. 4). Self-organization values in 2015 were located on the top of the regression line, indicating that the forest was highly self-organised.

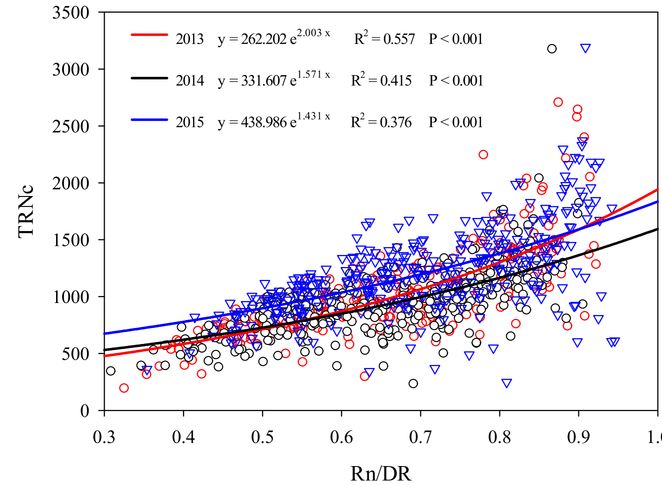

Fig. 4. Average annual patterns of self-organization (Net radiation/global radiation (Rn/DR), thermal response number of canopy temperature (TRNc).

3.3. Exergy capture ability and exergy dissipation ability

In general, the higher value for ability to capture exergy (Rn/DR) occurred during the most time in 2015 compared with 2013 ($P = 0.007$) and 2014 ($P = 0.003$) (Fig. 5a, Table 1). However, during the months of January and November 2015, the Rn/DR ability values are lower than the respective months of 2014 and 2013, respectively. The ability of capture exergy (Rn/DR) in 2015 increased by 6.28% and 7.24%, respectively, compared to pre-disturbance years.

For 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. TRNc in August of 2015 had the highest values (Fig. 5b, Table 1), and TRNc has extremely significant difference compared with pre-disturbance years. Exergy dissipation ability in 2015 increased by 20.65% and 28.75%, respectively, compared to pre-disturbance years. UR/DR (reflective radiation/global radiation) in 2015 was lower than that in other two years significantly ($P < 0.001$) (Fig. 5c, Table 1). UR/DR in 2015 decreased by 38% and 41.14%, respectively, compared to 2 pre-disturbance years. There were no significant differences ($P > 0.05$) in I/DR (net long wave radiation/global radiation) among the three years (Fig. 5d, Table 1).

4. Discussion

We used the thermodynamic approach developed by Lin et al. (2009) to evaluate the self-organization of the subtropical evergreen forest in response to snow disturbance that occurred in January 2015 (Fig. S1). Self-organization values in 2015 were located on the top of the regression line (Fig. 4), indicating that the forest was highly self-organised and the ecosystem was more developed. It would both gain more exergy and dissipate exergy more efficiently, increasing both in the Rn/DR and TRNc in 2015 (Fig. 5a-b).

The snow disturbance induced severe vegetation damage, as indicated by LAI significantly decreased by 33.19% and 40.85% in 2015 than the pre-disturbance years (2013–2014), respectively (Fig. 3, S2). Sharp increases (113%) of LAI were observed from August 2015(Fig. 3), but remained significantly lower than the level of the pre-disturbance years. Previously, tropical rainforest of Xishuangbanna, southwest China regions showed the lowest exergy capture capacity in the dry season, which coincided with the lowest LAI period (Lin et al., 2011). However, the decreases in LAI didn't affect the exergy capture capacity of the subtropical rainforest. Comparatively, our results showed that the snow disturbance ecosystem promoted the more self-organizing patterns with higher exergy capture capacity due to the fast growth of understorey bamboos (*Fargesia sp*) (Fig.S3) and tree seedlings due to the

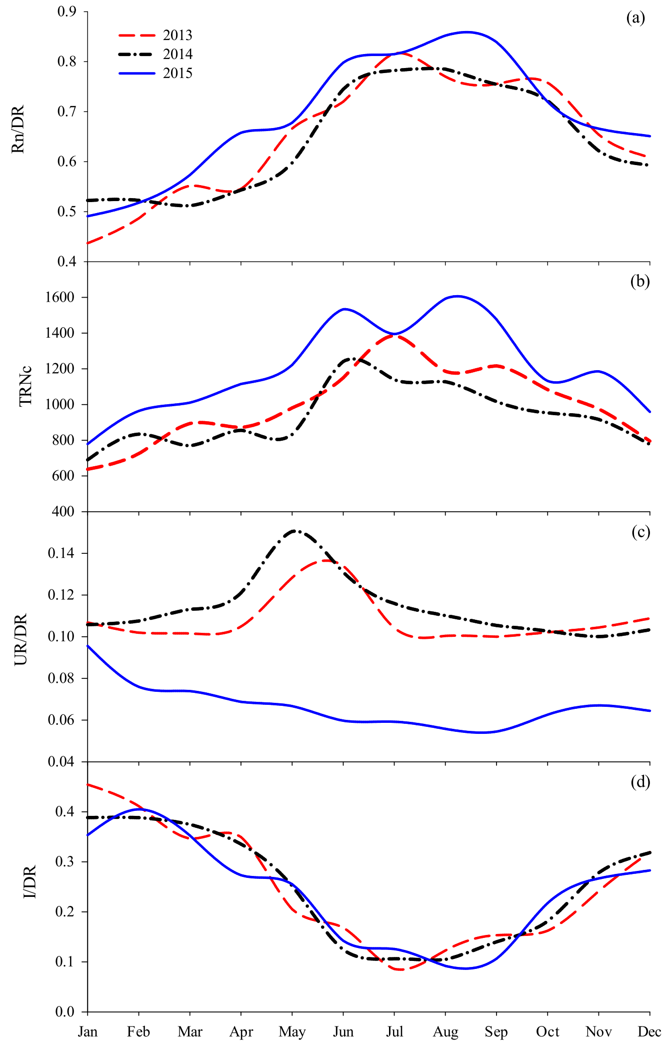

Fig. 5. Average annual fluctuations of net radiation/global radiation (Rn/DR), thermal response number of canopy temperature (TRNc), reflective radiation/global radiation (UR/DR) and net long wave radiation/global radiation (I/DR).

Table 1
The difference analysis of parameters between the year of snow damage (2015) and the pre-disturbance years (2013 and 2014). The values in parentheses are monthly averages and standard deviation for each parameter. (Net radiation/global radiation (Rn/DR), thermal response number of canopy temperature (TRNc), reflective radiation/global radiation (UR/DR) and net long wave radiation/global radiation (I/DR).

Parameters	year		t	P
Rn/DR	2015 (0.69 ± 0.12)	2013 (0.65 ± 0.12)	3.282	0.007
		2014 (0.64 ± 0.11)	3.846	0.003
TRNc	2015 (1197.34 ± 255.56)	2013 (929.99 ± 170.16)	5.971	<0.001
		2014 (992.39 ± 220.81)	7.722	<0.001
UR/DR	2015 (0.07 ± 0.011)	2013 (0.11 ± 0.01)	−8.417	<0.001
		2014 (0.11 ± 0.01)	−8.734	<0.001
I/DR	2015 (0.24 ± 0.10)	2013 (0.25 ± 0.12)	−0.850	0.413
		2014 (0.25 ± 0.11)	−1.167	0.268

canopy gap (Gnanamoorthy et al., 2021; Song et al., 2017b, 2018). Generally, subtropical forests have the reliance nature to recover faster from extreme snow disturbance (Gnanamoorthy et al., 2021; Song et al., 2017a; Zhang et al., 2015). Interactions between forest canopy and understorey vegetations characteristics are important contributors of forest ecosystems structure and dynamics (Ikawa et al., 2015; Taylor et al., 2004). Forest ecosystems with canopy gap have the well-developed understorey biomass, that play an important role in overall carbon sequestration (Paul-Limoges et al., 2017; Tan et al., 2012). Further, ensures this, understorey vegetations shows the maximizes radiation capture, and optimizes exergy dissipation compared to the pre-disturbance year (Gnanamoorthy et al., 2021).

The ways of exergy dissipation mainly include reflection loss and long-wave radiation loss. The rate of long-wave radiation is negatively correlated with exergy dissipation capability (Fig. 5). Reflection ratio have significant correlations with changes in vegetation pattern, evidently higher ratios occurred in sparse forest than the dense grassland (Lin et al., 2009). The reflectivity loss rate (UR/DR) of the ecosystem in 2015 was significantly lower than that in the pre-disturbance years while the long-wave radiation loss rate had little difference among the three years (Table 1). But the exergy dissipation in 2015 was higher than that in the pre-disturbance years (Table 1). The reason was probably that the canopy damage can trigger additional ecosystem disturbances, releasing soil carbon to the atmosphere due to the increase of soil temperature under the open canopy (Chen et al., 2017; Wu et al., 2014). The forest floor evaporation may also increase due to the canopy opening. Ecosystem evaporation and respiration became the important ways of exergy dissipation. Therefore, the forest exergy dissipation in 2015 was higher than pre-disturbance years. The higher exergy capture capacity and exergy dissipation capacity indicated that the ecosystem was more self-organized and well developed in 2015.

Our findings were inconsistent with the general theory that the disturbance of natural systems reduces exergy capture ability and increases exergy dissipation (Alvarenga et al., 2013; Wagendorp et al., 2006). Alvarenga et al. (2013) divided the earth into two systems, one is natural, and the other is man-made, to calculate exergy-based accounting for land as a resource in life cycle assessment (LCA). For the human made system, anthropogenic activities as the key factors, such as the over exploitation of resources, would decrease the exergy level of natural systems (Wagendorp et al., 2006). Zhang et al. (2012) studied in subtropical forests of Southern China showed the snow damaged forest ecosystem acted as a carbon source to the atmosphere for a short period. Further, the severe drought stress also reduced the level of self-organization in a tropical rainforest (Song et al., 2013). In this connections, different kinds of forest disturbance such as, hurricane, forest fire, beetle attack, drought and extreme snow fall, affect the overall ecosystem carbon balance and energy exchanges by altering the rates of carbon sink ability and radiation reflectance, which could create the positive feedback to forest ecosystem (Barr et al., 2012; Chang et al., 2020; Gnanamoorthy et al., 2021; O'Halloran et al., 2012; Potter et al., 2020). Generally, more studies are still needed on above mentioned disturbance to explore the different forests self-organization pattern.

5. Conclusion

In this study, we assessed the self-organization of subtropical evergreen broad-leaved forests after the snow damage. We found that self-organization values in 2015 were higher, indicating that the forest was highly self-organised. In conclusion, alteration in vegetations patterns due to the snow disturbance of 2015 in the primary subtropical evergreen forest enhanced the self-organization. We suggest that long-term monitoring should be continued to better understanding the sustained effects of snow disturbance to self-organization and explore the different forests self-organization pattern based on different disturbance.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2021.101482.

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