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ORIGINAL PAPER

Comparison of infrared canopy temperature in a rubber plantation and tropical rain forest

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Abstract Canopy temperature is a result of the canopy energy balance and is driven by climate conditions, plant architecture, and plant-controlled transpiration. Here, we evaluated canopy temperature in a rubber plantation (RP) and tropical rainforest (TR) in Xishuangbanna, southwestern China. An infrared temperature sensor was installed at each site to measure canopy temperature. In the dry season, the maximum differences ($T_c - T_a$) between canopy temperature (T_c) and air temperature (T_a) in the RP and TR were 2.6 and 0.1 K, respectively. In the rainy season, the maximum ($T_c - T_a$) values in the RP and TR were 1.0 and −1.1 K, respectively. There were consistent differences between the two forests, with the RP having higher ($T_c - T_a$) than the TR throughout the entire year. Infrared measurements of T_c can be used to calculate canopy stomatal conductance in both forests. The difference in ($T_c - T_a$) at three g_c levels with increasing direct radiation in the RP was larger than in the TR, indicating that change in ($T_c - T_a$) in the RP was relatively sensitive to the degree of stomatal closure.

Keywords Surface temperature · Tropical · Rainforest · Rubber plantation · Climate change

Introduction

Infrared canopy temperature (T_c) measurements can be conducted rapidly and efficiently, and are an alternative to conventional methods, such as stomatal conductance (g_c) or stem water potential measurements, for monitoring plant water status in different agricultural and forest ecosystems (Leuzinger and Köner 2007; Wang and Gartung 2010; Maes et al. 2011; Scherrer et al. 2011; Ballester et al. 2013). For example, when crops are managed under deficit irrigation, infrared thermometry can provide useful information regarding surface temperature for supporting variable-rate irrigation in time and space and identification of irrigation zones (Alchanatis et al. 2010; Cohen et al. 2011). Canopy foliage temperature is a comprehensive result of plant traits, energy balance, and environmental factors (Scherrer et al. 2011). Therefore, different plant species or communities are highly variable in T_c due to biotic and abiotic variables, which might have different cooling effects.

Plants under soil water deficit often decrease g_c, resulting in reduced transpiration and increased leaf temperature. Therefore, g_c plays an important role in plant–atmosphere water exchange. Instruments such as infrared gas analyzers or porometers have been used to determine the stomatal opening (Zhang et al. 2007; Chen 2008; Zhang et al. 2013, 2014) by measuring the transpiration rate on a small portion of leaves. However, these measurements are labor intensive and non-automated, which limits the spatial and temporal coverage of g_c assessments. In addition, using

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these methods, it is difficult for technicians to sample the canopy leaves of dominant tree species and measure the leaf g_c in tropical forests with old trees and a high canopy (Leuzinger and Köner 2007; Scherrer et al. 2011). Fortunately, previous studies have shown that with a few supplemental measurements and application of biophysical principles, infrared measurement of T_c can be used to calculate canopy g_c (Leinonen et al. 2006; Blonquist et al. 2009; Leuzinger et al. 2010).

Xishuangbanna, located at the northern edge of tropical southwestern Asia, is a transitional area between the tropics and the subtropics. The area is considered to be particularly sensitive to the impacts of climate change (Tan et al. 2013; Zhang et al. 2015), such as changes in temperature and precipitation patterns. Climate records at Xishuangbanna over the past 40 years have shown a significant increase in air temperature (T_a). A previous study showed that the expansion of rubber plantations and the reduction of tropical seasonal rainforest would likely induce local surface warming and larger ranges in daily temperature (Lin et al. 2009). Monoculture rubber plantations and primary tropical forests are highly variable in physiological traits related to the water balance. Therefore, the change in T_c in relation to the responses of the two communities to expected climate change might also be variable.

The objectives of this study were to (1) to quantify the differences in magnitude and seasonal dynamics of T_c in the two forest ecosystems, (2) evaluate the usefulness of thermography for the estimation of canopy g_c, and (3) discuss differences in T_c between the two forest ecosystems in a changing climate.

Site and methods

Site describe

The tropical rainforest study site (TR) (21° 55′ 39″ N, 101° 15′ 55″ E, 750 m a.s.l.) is located in the Menglun Nature Reserve in Xishuangbanna, southwestern China (Fig. 1).

The site is located at the northern edge of tropical southwestern Asia, and is a transition area between the tropics and the subtropics (Zhang 1966; Cao et al. 1996). The dry season occurs between November and April. Dominant tree species are *Pometia tomentosa*, *Terminalia myriocarpa*, *Gironniera subaequalis*, and *Garuga floribunda*, which can exceed 40 m in height (Fig. 2). The soil is lateritic derived from siliceous rocks, such as granite and gneiss, with a pH from 4.5 to 5.5.

The rubber plantation study site (RP) is located in the experimental area of the Xishuangbanna Tropical Botanical Garden (21° 55′ 30″ N, 101° 15′ 59″ E; elevation 570 m a.s.l.), Xishuangbanna, Yunnan Province, southwestern China (Fig. 1). Rubber plantations (*Hevea brasiliensis*) have been replacing primary TR with dramatic speed in recent years in China (Song et al. 2013). The study site is included in a large 36-year-old rubber plantation. The rubber plantation has a mean canopy height of approximately 22 m (Fig. 2).

The two sites are located about 10 km apart and share similar climate conditions. According to climatic observations at a meteorological station over the past half century (1959–2008), the mean annual temperature is 21.8 °C, and the mean annual rainfall is 1511 mm. Over 85% of the annual rainfall occurs in the rainy season. The mean monthly rainfall during the dry season is less than 40 mm.

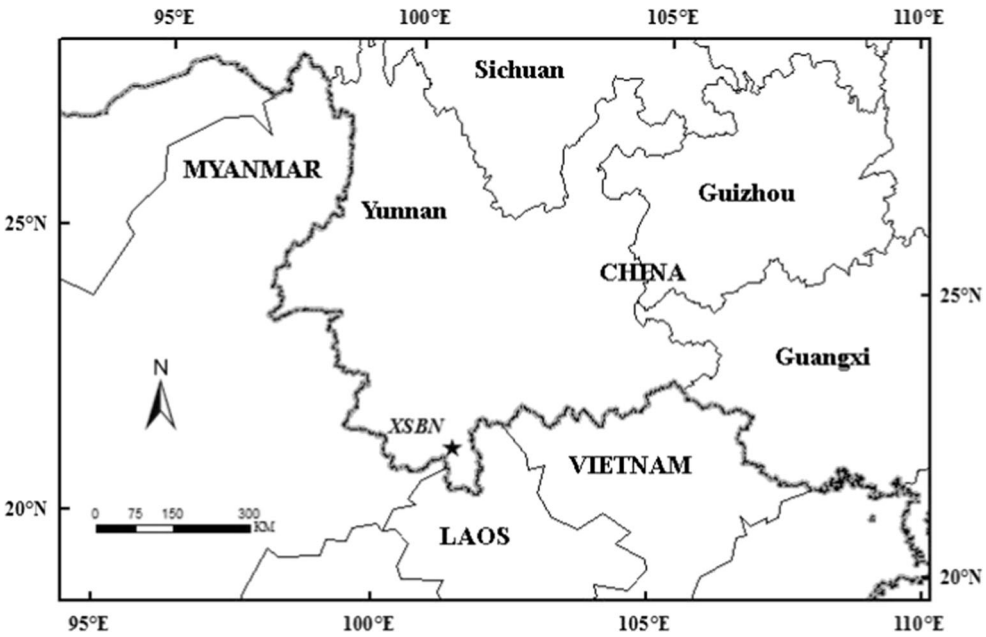

Fig. 1 Location of the study site (*XSBN*: Xishuangbanna)

Fig. 2 Canopy pictures of the rubber plantation and the tropical rainforest

Measurement of meteorological factors and T_c

Instruments for measuring T_a, air humidity (RH) (HMP45C, Vaisala, Helsinki, Finland), and wind speed (W_s) (A100R, Vector Instruments, Denbighshire, UK) were installed on the observational tower at each site. Radiation sensors for downward and upward, short- and long-wave radiation (CNR-1/CM11, Kipp & Zonen, Delft, Netherlands) were installed on a horizontal pole 3 m from the tower at each site. Profiles of soil moisture were measured at different depths (5, 10, 20, 40, 60, and 100 cm) (105 T/107 L, Campbell, Logan, UT, USA) at each site. Meteorological data were collected every 30 min at each site using a CR1000 (Campbell).

An infrared temperature sensor (SI-111, Apogee Instruments, Inc., Logan, UT, USA) was installed at each site to measure T_c. The sensor was installed on an observational tower and mounted on 4-cm-diameter galvanized metal pipes positioned 3.0 m above each forest canopy. The sensor was aimed at the canopy, with view half angles of approximately 22°from nadir. The absolute accuracy of the sensor is ±0.2 °C. The radiation detected using an infrared radiometer includes two components: (1) the radiation directly emitted by the target surface, and (2) reflected background radiation. The second component is often neglected. The magnitude of the two components in the radiation detected by the radiometer is estimated using the emissivity and reflectivity of the target surface (Blonquist et al. 2009).

Leaf area index measurement

Leaf area index (LAI) was measured using a canopy analyzer (Model LAI-2000, LI-COR, Lincoln, NE, USA). We measured the background value (termed A value by LAI-2000) at the top of the tower in the TR (70 m) and the RP (55 m). The LAI at different heights was measured at platform locations on the towers. On each platform, 15 points were sampled in different directions to eliminate the tower shadow effect. The LAI was measured monthly in the two sites.

Calculating canopy stomatal conductance

H_C is sensible heat flux and λE_C is latent heat flux. The terms H_C and λE_C can be expressed as (Campbell and Norman 1998)

$$\mathrm{Hc} = g_H C_p (T_c - T_a) \tag{1}$$

$$\lambda E_C = g_T \lambda \left(\frac{\mathrm{VPD}}{P_a}\right) \tag{2}$$

where g_H is the boundary layer heat conductance (mmol m^{-2} s^{-1}), Cp is the specific heat of air at constant pressure (J mol^{-1} K^{-1}), gT is the total water vapor conductance (mmol m^{-2} s^{-1}), λ is the latent heat of vaporization (J mol^{-1}), VPD is the vapor pressure deficit (kPa), and Pa is the atmospheric pressure (kPa)

$$\mathrm{gT} = \frac{1}{\left(1/\mathrm{gH}\right) + \left(1/\mathrm{gc}\right)} \tag{3}$$

Combining Eqs. (1)–(3) and rearranging to solve for canopy g_c (mmol m^{-2} s^{-1}) (Blonquist et al. 2009) yields

$$\mathrm{gc} = \frac{gHPa[(\mathrm{Rn}-\mathrm{G}) - gHCp(\mathrm{Tc}-\mathrm{Ta})]}{\mathrm{gH}\lambda\mathrm{VPD} - \mathrm{Pa}[(\mathrm{Rn}-\mathrm{G}) - gHCp\mathrm{VPD}]} \tag{4}$$

where P_a is the atmospheric pressure (kPa), R_n is the net radiation (W m^{-2}), and G is the soil heat flux (W m^{-2}).

Based on the terms of the Monin–Obukhov similarity theory (Monin and Obukhov 1954), g_H is discerned between conductance of heat and the boundary layer conductance of water vapor.

Analysis method

A multiple correlation regression analysis (SPSS 22.0 Software, SPSS Inc. 2013, IBM, Armonk, NY, USA) was used for the stepwise selection of the dominant drivers of g_c during the dry season, rainy season, and whole year. The drivers for g_c, as included in this analysis, were solar radiation (DR), T_a, vapor pressure deficit (VPD), and W_s. The dominant

variables for each regression were chosen by a stepwise procedure. The coefficients and their relative contributions are presented for each variable.

Results

T_c variability

Figure 3 shows T_a, T_c, and the diurnal canopy to air temperature difference ($T_c - T_a$) during the dry season (March–April) and rainy season (July–August) in 2011 at the two sites.

In general, the variation patterns of T_a in the same season at the two sites were similar (Fig. 3). However, T_c was different at the two sites in the same season. The value of canopy to air temperature difference ($T_c - T_a$) at the RP was higher than the TR throughout the entire study period. During the dry season, the daily peak value of ($T_c - T_a$) at RP appeared to occur at approximately 12:00 h (Fig. 3a), while the daily peak value of ($T_c - T_a$) at TR appeared to occur at 13:00 h (Fig. 3b). The maximum ($T_c - T_a$) values at the RP and TR in the dry season were 2.6 and 0.1 K (Fig. 3a, b), respectively. During the rainy season, the daily peak value of ($T_c - T_a$) at the RP appeared to occur at approximately 13:00 h, while the peak value at the TR appeared around 15:30 h. During nighttime, ($T_c - T_a$) at the TR was significantly lower than the RP. The maximum ($T_c - T_a$) values at the RP and TR in the rainy season were 1.0 and −1.1 K, respectively.

Infrared temperature for estimating canopy stomatal conductance

Continuous estimation of canopy g_c based on the infrared temperature at both study sites is shown in Fig. 4. g_c showed clear seasonal patterns in RP. g_c was nearly zero during the leafless period at the end of the foggy-cool season (Fig. 4), and then g_c increased sharply with leaf emergence in the early dry-hot season. g_c reached a high plateau during the rainy season. The value of g_c peaked after the leaf flush, and the maximum g_c was about 750 mmol m^{-2} s^{-1} in the rainy season. g_c became lower with leaf senescence and then declined rapidly during leaf fall (Fig. S1).

In general, g_c also showed a seasonal pattern in TR. However, g_c showed a higher day-to-day variation than in the RP during the rainy season.

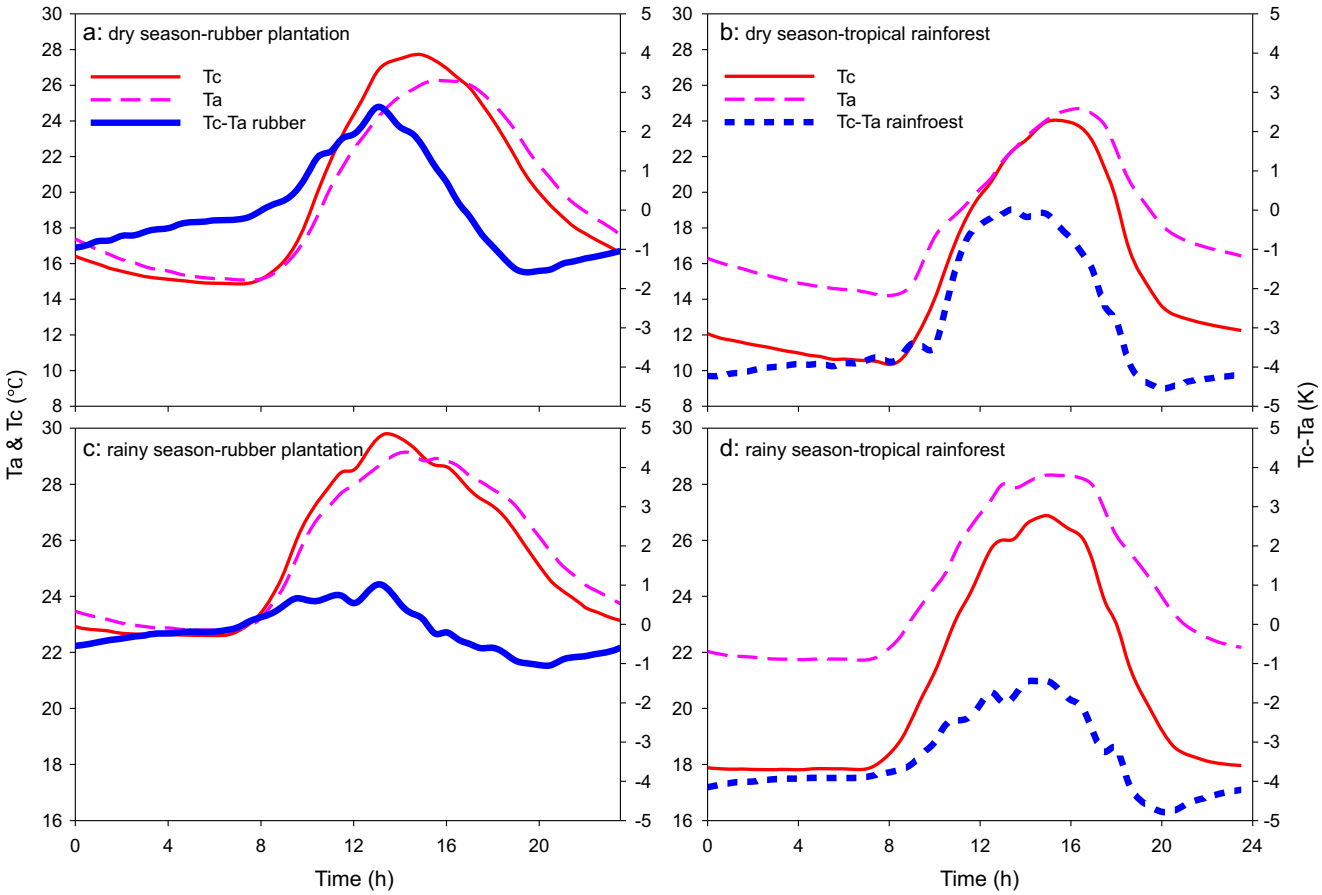

Fig. 3 Mean diurnal time series of air to canopy temperature difference during dry and rainy seasons in 2011 at the rubber plantation and tropical rainforest sites (**a** dry season rubber plantation; **b** dry season tropical rainforest; **c** rainy season rubber plantation; **d** rainy season tropical rainforest)

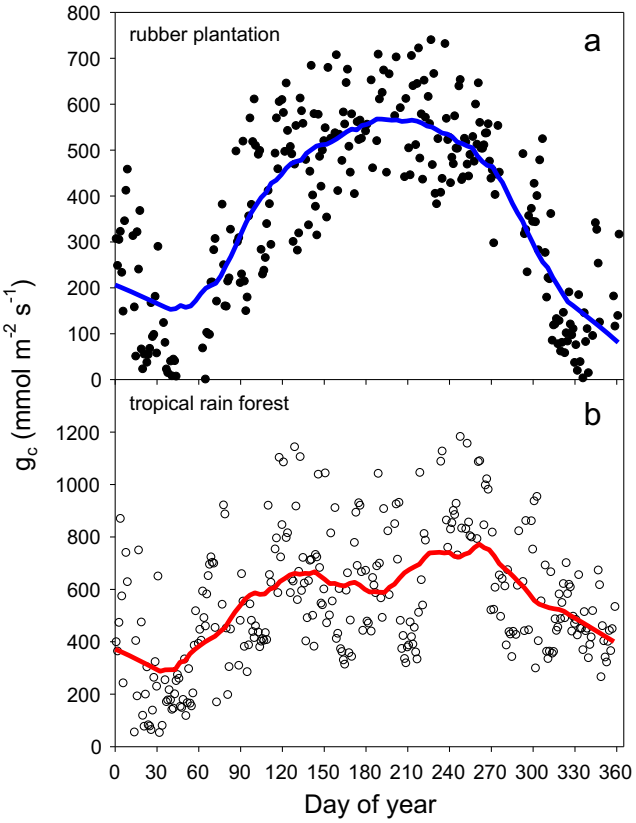

Fig. 4 Continuous estimation of canopy stomatal conductance (g_c) based on infrared temperature in the rubber plantation (**a**) and tropical rain forest (**b**). The values are average of six half-hour averages from 12:00 to 15:00 h. The *blue* and *red lines* represent daily average over daytime

We derived the energy balance for a plant canopy to calculate canopy stomatal conductance from measured meteorological and plant variables, which provided field-scale measurements of daily and seasonal stomatal response to local climate conditions.

To more deeply explore the influence of microclimate factors on g_c under the varying climatic conditions, we evaluated the correlations of environmental conditions with g_c on a statistical basis during the dry season and rainy season and over the entire year in RP and TR.

Multivariable correlations between g_c and microclimate conditions are shown in Table 1. The analysis defines the relative contribution of each parameter to g_c. T_a is the primary factor correlated with g_c during the dry season in the two sites. The relative contributions of each parameter to g_c were similar in the two forests. During the rainy season, VPD was the most important variable ($\beta\% = 57\%$) in the TR, but T_a was still the most influential ($\beta\% = 40\%$) in the RP. The relative contribution of T_a and RH were almost equivalent in the two forests. The two climate variables, T_a and VPD, contributed a total of 80% of the variations to g_c in the two forests over the entire year.

$T_c - T_a$ variations in a changing climate

To discuss possible effects of a changing climate on canopy-to-air temperature differences in the future, we solved Eq. 5 to evaluate the variations of T_c:

$$\mathrm{Tc–Ta} = \frac{\mathrm{Pa(Rn\ –G)–gc\lambda\ VPD\ } + (\mathrm{gc/gH})\mathrm{Pa(Rn–G)}\Big]}{gcCp + gHCp\mathrm{VPD}} \quad (5)$$

Increasing drought frequency has the potential to affect the carbon and water cycle in forest ecosystems. Warmer global temperatures are expected to cause an intensification of the hydrologic cycle, with increased evaporative demand in ecosystems. As mentioned above, plants under drought stress decrease stomatal conductance, thereby reducing transpiration and increasing T_c. Therefore, to explore the differences in T_c between RP and TR in an expected changing climate, we assumed a decrease by 25, 50, and 75% of maximum g_c values at both sites.

In order to better evaluate the difference of T_c in the two forests, ($T_c - T_a$) was normalized by T_a ([$T_c - T_a$]_normalized). ($T_c - T_a$)_normalized was very sensitive to all simulated meteorological conditions (Fig. 5) and increased linearly with increasing DR. ($T_c - T_a$)_normalized decreased non-linearly with

Table 1 Coefficients (B) and relative contributions (β%) of meteorological parameters with g_c of the rubber plantation (RP) and tropical rainforest (TR) in different periods

	Dry season				Rainy season				Whole year			
	RP		TR		RP		TR		RP		TR	
	B	β%	B	β%	B	β%	B	β%	B	β%	B	β%
DR	−0.1	18*	−0.3	5	−1.0	20**	0.1	10*	−0.9	12**	−0.7	13*
T_a	50.0	51**	31.4	51**	54.9	40**	4.2	24**	57.0	60**	23.6	52**
VPD	−268.9	29**	−267.0	39**	−315.8	33**	−22.4	57**	−328.0	24**	−70.6	28**
W_s	32.3	2	−189.9	5	60.4	7	79.2	9*	53.9	4	−267.0	7

*Significant difference for the parameter between the different periods at the 0.05 significance level; **difference at the 0.01 significance level

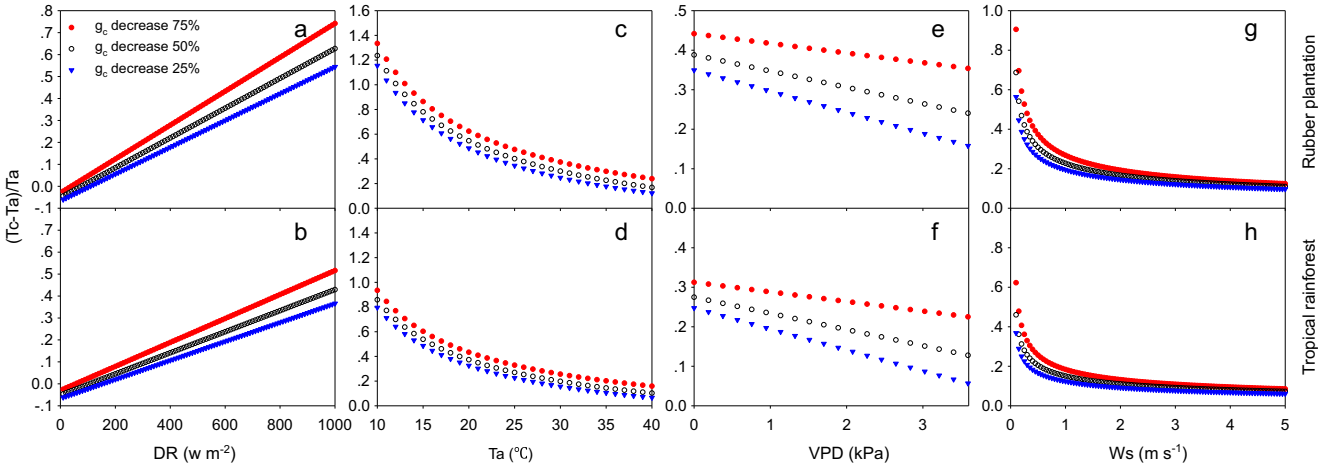

Fig. 5 Influence of climate conditions on (T_c − T_a)_normalized, including direct radiation (DR), air temperature (T_a), vapor pressure deficit (VPD), and wind speed (W_s), for three levels of g_c at the rubber plantation (**a**, **c**, **e**, **g**) and the tropical rainforest sites (**b**, **d**, **f**, **h**)

increasing T_a and W_s (Fig. 5). (T_c − T_a)_normalized increased sharply with DR in all g_c levels and at all sites. At the same level of g_c, (T_c − T_a)_normalized had a steeper increase in relation to increasing DR in RP than in TR (Fig. 5a, b) on average, approximately 2 K higher than in TR. However, the difference in (T_c − T_a)_normalized at three g_c levels with increasing DR in RP was larger than in TR, indicating that change in the (T_c − T_a)_normalized in RP was relatively sensitive to the degree of stomatal closure. In contrast, the difference in (T_c − T_a)_normalized at the three g_c levels in TR became smaller with increasing DR.

(T_c − T_a)_normalized showed a completely opposite pattern than that of increasing T_a and VPD (Fig. 5c–f), indicating that (T_c − T_a)_normalized decreased with increasing VPD. Similarly, the difference of (T_c − T_a)_normalized at three g_c levels with increasing T_a in TR was small, while the difference was large in RP. In TR, (T_c − T_a)_normalized decreased slightly with increasing T_a, indicating that (T_c − T_a)_normalized did not particularly depend on T_a at low g_c levels. In contrast, (T_c − T_a)_normalized was highly sensitive to increasing T_a in TR due to a relatively more opened stoma and higher canopy transpiration.

Discussion

Our results showed constant difference between the two forests, with the RP having a higher (T_c − T_a) than the TR throughout the whole year. The greater heating of canopy leaves in RP is likely the result of general low canopy g_c, leading to low transpirative cooling. Plants under soil water deficit decrease g_c, thereby reducing transpiration and increasing leaf temperature. Previous study has shown that canopy transpiration for dominant tree species in the dry season was lower than in the rainy season at both sites (Song et al. 2013). The reduction in transpiration in the dominant canopy trees during the dry season (with high evaporative demand) could partly explain the increase of canopy to T_a difference. Our results were consistent with thermodynamic principles that posit that a more "developed" ecosystem should have relatively lower surface temperature than a less developed equivalent (Schneider and Kay 1994; Lin et al. 2009).

Canopy g_c has been used as a parameter to express the physical effect of stomatal movement at the canopy scale (Maruyama and Kuwagata 2008; Zhang et al. 2011). Infrared T_c measurements provided a useful evaluation of canopy conductance in monoculture plantation and primary TR in this study. The maximum g_c in the RP was higher than the value (500 mm m^{-2} s^{-1}) in a teak plantation in Northern Thailand (Igarashi et al. 2015). The maximum g_c in TR was similar with the g_c (1200 mm m^{-2} s^{-1}) in a tropical forest in Nigeria (Grace et al. 1982). With the estimated LAI, we transferred g_c (mmol m^{-2} s^{-1}) to stand-level conductance (mm s^{-1}, g_s). The maximum g_s in TR was about 2.70 mm s^{-1}, which was higher than the average g_s (2.2 mm s^{-1}) in a tropical forest in Brazil (Pereira et al. 2010) and similar with the average g_s (2.67 mm s^{-1}) in an olive orchard in southern Spain (Testi et al. 2006).

In addition, infrared T_c measurements are automatic and effective, providing an alternative option to conventional methods, such as stomatal conductance or stem water potential measurements, in monitoring plant water status (Wang and Gartung 2010; Ballester et al. 2013), especially in the tropical forests with a high canopy. For example, the LAI of RP during the rainy season was about 3.9–4.6 m^2 m^{-2}. Daily g_c mean values during the rainy season (per projected leaf area) (500–750 mmol m^{-2} s^{-1}) in RP were typically about three to five times that of the single leaf values (per projected leaf area, 100–180 mmol m^{-2} s^{-1}) (Chen 2008). This is consistent with the finding that canopies with multiple leaf layers have higher conductance than single leaves due to the sum of contributions from the single leaves (Blonquist et al. 2009). Our results also

support the big-leaf model theory, which maps properties of the whole canopy onto a single leaf (Zhang et al. 2011). However, monitoring T_c with the infrared temperature sensor in a fixed position only partially covers the canopy, and the data are too limited to account for variations in the entire canopy and differences between species, particularly for the high diversity tropical forest in this study. Previous study has also shown that canopy architecture has a consistent influence on canopy foliage temperature, in that "dense canopy" species are warmer than "open canopy" species in a mixed temperate forest (Scherrer et al. 2011). In contrast, we can see that the canopy is not always continuous in the forest and some canopy gaps are embedded in the community. Monitoring T_c with the infrared temperature sensor might include information from big branches and the forest floor. In addition, the temperature of shaded leaves is lower than the sunlit leaves of the same trees (Ballester et al. 2013).

As mentioned previously, the TR canopy is uneven and complex and can be divided into three layers. The fixed infrared sensor cannot measure the lower layer temperature, resulting in an underestimation of the actual leaf temperature of fully sun-exposed leaves, and therefore, it presented mean canopy foliage temperature in TR. Furthermore, the higher day-to-day variation in TR suggested that this fact could be due to the difficulty of relating the average temperature of multiple differently oriented leaves with stomatal conductance of individual ones. In this study, the canopy of RP was more flat and homogenous, and the use of T_c measurements to detect canopy g_c appeared to be more precise in RP than in TR. It appeared that g_c in TR showed higher day-to-day variation than in RP during the rainy season, indicating that the high tree species diversity in TR influenced the final canopy g_c pattern. g_c may strongly depend on canopy architecture (leaf area density, branching habits, and canopy height) in combination with leaf traits. For the tall forest, it has been shown that transfer coefficients of different layers may differ quite significantly during the daytime (Raupach 1979; Viswanadham and Sa 1987). Below the canopy, the flow is likely to be influenced by thermal effects directly attributable to the surface (Raupach 1979). Therefore, the different layers of tall forests should be considered in future studies.

Despite the fact that the two sites shared similar climate conditions, stand structure and topography also impacted the difference between T_c and T_a. On a daily scale, T_c increased rapidly as soon as the sun struck the canopy. The canopy of the TR, which was located in a valley, warmed slowly in the morning and cooled rapidly in the evening.

In addition, characterizing infrared sensor noise is imperative for ensuring that thermal fluctuations are attributable to the forest canopy (Aubrecht et al. 2016). Estimation of canopy stomatal conductance can be improved by dividing the canopy into sunlit and shaded leaves (Wang and Leuning 1998; Irmak et al. 2008). Also, there was no correction for evaporation of intercepted water and fog/cloud drip and the effect of canopy cooling during the rainy season or part of the dry season. Intercepted water, fog drip, and cloud shading regulate the forest water balance, VPD, and vegetation g_c. Suppressed incoming radiation and transpiration rates during the fog period of the dry season may be favorable for low water use in these study sites. Future work is needed to improve estimates of the variation in canopy conductance on a fine spatial scale and diurnal and seasonal time scales (Aubrecht et al. 2016).

Normalized $(T_c - T_a)$ was very sensitive to all simulated meteorological conditions. Normalized $(T_c - T_a)$ increased linearly with increasing DR and decreasing VPD. Normalized $(T_c - T_a)$ also decreased non-linearly with increasing T_a and W_s. Our simulation results were consistent with research by Maes et al. (2011), Maes and Steppe 2012). Overall, T_c in the RP and TR responded differently to the changing climate. The change in T_c was controlled by the climate, but plant-inherent traits, such as g_c, also played an important controlling role. Despite the fact that infrared T_c measurements can be used as a water stress indicator, there has yet to be a critical assessment of the relationship between T_c and plant species composition, canopy structure, and leaf functional traits.

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Compliance with ethical standards

Competing interests The authors declare that there are no competing interests.

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