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# The importance of radiation fog in the tropical seasonal rain forest of Xishuangbanna, south-west China

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## ABSTRACT

The tropical rain forest in Xishuangbanna, SW China has a high floristic diversity and is closely related to Malaysian rain forests in flora. This forest would not normally be established in such a climatic region as Xishuangbanna (less precipitation and lower air temperature) compared to those of the lowland moist tropics. The mean annual rainfall is 1487 mm, which is considerably lower than rain forests in other parts of the world. It is believed that the frequent occurrence of radiation fog might play an important role in the water relations of plants and in the hydrological cycle of this type of rain forest. However, the multiple hydrological and ecological effects of radiation fog are not well understood. In this paper, we describe and analyze the significance of radiation fog to this forest, and develop a hypothesis that fog plays an important role in the presence of the tropical rain forest in Xishuangbanna. Suggestions for further research on the significance of fog are offered.

**Key words** | hydrological cycle, radiation fog, south-west China, tropical seasonal rain forest

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## INTRODUCTION

The Xishuangbanna forest reserve (21°09′–22°33′N, 99°58′–101°34′E) is situated on the northern edge of the tropical zone in South-East Asia contiguous to Laos to the south and Myanmar to the southwest. This area constitutes an intermediate zone between continental mainland Asia and the South-East Asian Peninsula, reflecting the interlacing of the flora from both the south and the north (Cao *et al.* 1996).

With direct impacts of the East Asian Monsoon, Xishuangbanna is dominated by warm-wet air masses from the Indian Ocean and the Bay of Bengal in summer (south-west monsoon) and continental air masses of subtropical origin in winter (Zhang 1986). The mean annual rainfall is 1487 mm, which is considerably lower than rain forest in other parts of the world. The Hengdwan Mountains to the north of the region act as a major barrier keeping out cold air coming from the north in the winter. During the dry season (November–April), a daily 'sea of fog' commonly develops between altitude 500 m and 1,500 m in wet valleys and on low hills. Due to its unique geographical location and climatic features, this area supports a tropical rain forest with a small proportion of deciduous tree species (Cao *et al.* 1996). According to the classification system of the vegetation in China (Wu *et al.* 1987), there are five primary forest vegetation types in this area: tropical seasonal rain forest, tropical montane rain forest, evergreen broad-leaved forest, monsoon forest over limestone, and monsoon forest on river banks. A large proportion of the forest in this region is tropical seasonal rain forest. The seasonal rain forest is primarily formed in wet valleys, lowlands and on low hills (less than 1,000 m above sea level) where heavy radiation fogs frequently occur. The tropical rain forest differs from tropical Asian lowland rain forests in that some of its tree species are deciduous. Species richness is lower than those of Malaysian rain forests, but higher than those of Australian and African rain forests, and similar to tropical forests on Barro Colorado Island, Panama (Cao *et al.* 1996).

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Rainfall dominates the moisture input to the rain forest, but it is recognized that clouds and fog may be important sources of water for some forests occurring at higher altitudes (Grubb & Whitmore 1966; Hamilton 1995). Fog drip, the coalescing of fog droplets on foliage producing large drops which fall to the ground, has been observed by researchers for many years (Harr 1982; Aravena *et al.* 1989; Ingraham & Matthews 1990; Bruijnzeel & Proctor 1995; Bruijnzeel & Veneklaas 1998; Dawson 1998; Bruijnzeel 2001). Past investigations have shown that water input and soil moisture is measurably higher under the tree canopies and in forest stands where the fog is stripped from the air mass (Vogelmann *et al.* 1968; Ingwersen 1985; Schemenauer *et al.* 1988; Dawson & Ehleringer 1991; Scholl *et al.* 2002) and that when trees are lost or removed from the watershed, both the water input from fog drip and the streamflow decline significantly (Harr 1982; Ingwersen 1985). Other studies demonstrated that ecosystem nutrient balance and ecosystem biogeochemistry could also be influenced by fog water inputs (Lovett *et al.* 1982; Bruijnzeel *et al.* 1993; Weathers & Likens 1997; Clark *et al.* 1998; Song *et al.* 1999). Fog may help ameliorate plant moisture stress by reducing canopy transpiration or evaporation from the habitat (Hutley *et al.* 1997).

Within the tropical seasonal rain forests of Xishuangbanna, it has been speculated that radiation fog might play an important role in the water relations of plants and in the hydrological and biogeochemical cycles (Cao *et al.* 1996). Despite these acknowledgments, there are few data available on the hydrological and chemical contributions of radiation fog to this forest. This paper focuses on developing a testable hypothesis that fog plays an important role for the presence of the tropical rain forest in Xishuangbanna, i.e. a fog hypothesis, and offers some suggestions for further research.

## GENERAL CLIMATIC CONDITIONS AND FOG FREQUENCY

Long-term climate records (1959–2002) as measured at a weather station (600 m *asl*) 5 km SE from the tropical seasonal rain forest site (dominated by *Pometia tomentosa* and *Terminalia myriocarpa*; 750 m *asl*) showed that the prevailing wind direction is SW all year round, the mean annual wind speed is 0.7 m/s, and the frequency of calm days is 75%. The mean annual air temperature is 21.7°C with a maximum monthly temperature of 25.7°C for the hottest month (June) and a minimum monthly temperature of 15.9°C for the coldest month (January) (Liu *et al.* 2004). The temperature could exceed 38°C during March and April, and is always associated with a low relative humidity (less than 40%). There is a distinctive dry season and wet season during the year (Zhang 1986). The dry season could be subdivided into a cool-dry (from November to February) and a hot-dry (from March to April) sub-seasons. The cool-dry sub-season is characterized by the highest frequency of heavy radiation fog during the night and morning. The hot-dry sub-season is characterized by dry and hot weather during the afternoon and with heavy radiation fog during the morning only. A rainy season occurs from May to October, and is characterized by high rainfall, which is mainly brought by the southwestern summer monsoon. The mean annual rainfall in the past 40 years is 1487 mm, of which 1294 mm (87%) occurs in the rainy season vs. 193 mm (13%) in the dry season. Class-A pan evaporation varies between 1000 and 1200 mm/yr. The mean monthly relative humidity is 87%.

Radiation fog occurred almost every day from November to April and was heaviest from midnight (2300–0200 h) until mid-morning (0900–1100 h), with fog frequency up to 90% in the cool-dry season (November–February) and 79% in the hot-dry season (March–April) (Liu *et al.* 2004, 2005*b*). During fog events, vegetation was covered by water drops, and beneath the canopy, the ground was commonly wet. Generally, fog events were more frequent and longer during the cool-dry season than during the hot-dry season. Notably, fog frequency was quite low during the rainy season (May–October) compared to the dry season. Daily average duration of fog in the cool-dry season was 12.2 h, being 1.2 and 1.8-fold longer compared to the hot-dry and rainy season, respectively. These data correspond to fog occurring during 46, 35 and 15% of the time during the three seasons, respectively.

At the tropical seasonal rain forest site, the number of fog days per year was 258 d/yr, which can be compared to data from some cloud forest studies in the tropics. Gordon *et al.* (1994) found that the number of fog days was 326 and 310 days of the year at two Venezuelan cloud forests (Altos de Pipe, 1,750 m, and El Avila, 2,150 m) directly adjacent to the Caracas Valley, respectively. Similarly, Sugden (1986) reported that during the period of 271 observation days only on seven occasions were clouds absent from the summit of Cerro Copey (930 m), Margarita Island, Venezuela. Further west in Serrania de Macuira (730 m), Colombia, Sugden (1982) reported that during a three-month study fog was present on 95% of the nights observed, averaging 12.5 hours per day. At our rain forest site, the annual number of fog days was found to be negatively correlated with annual rainfall ($R^2 = 0.92$). This would suggest that fog may be of greater importance during the dry years.

## WATER INPUT FROM FOG DRIP

Earlier investigators of fog precipitation have estimated rates of fog impaction on artificial collectors (Ekern 1964; Goodman 1985; Cavelier & Goldstein 1989). The measurement made by a fog gauge depends on its position, nearby obstacles and wind conditions (Bruijnzeel 2001). Because of the structural complexity of the forest canopy, the results obtained by artificial fog gauges cannot readily be extrapolated to fog capture by an actual forest canopy (Lovett *et al.* 1982; Bruijnzeel 2001).

The net contribution of fog water to the forest floor could be estimated by measuring fog drip underneath the canopy during rainless periods only (Cavelier & Goldstein 1989; Holder 2003) or by comparison of amounts of canopy drip with amounts of bulk precipitation (Bruijnzeel & Proctor 1995; Bruijnzeel 2001). In our previous study (Liu *et al.* 2004), plastic funnel collectors (80 cm in diameter) each connected to a 1000 ml container were mounted at 0.7 m above the forest floor to collect fog dripping from the canopy. Twelve of these collectors were placed in a fixed but random pattern on the forest floor to determine the spatial variation of fog drip. The collectors were read every morning after fog drip had stopped, and were leveled and cleaned of any litter present. If rain occurred in the preceding night, no data were collected on the following morning. This may have slightly underestimated the amount of annual fog drip. However, in Xishuangbanna, days with night rain generally do not have radiation fog the following morning (Liu & Li 1996). Thus, the missed amount of fog drip should constitute a very small proportion of total annual fog drip. But, we could not rule out the possibilities that underestimates may have occurred due to the fact that fog drip was not recorded and accounted for on rainy days. Our study (Liu *et al.* 2004) showed that during a four-year period of observation (1999–2002), the average annual fog drip was 89.4 mm, accounting for about 5% of the annual rainfall (Table 1), which falls within the lower range of values compared to other tropical montane forests (Bruijnzeel & Proctor 1995; Bruijnzeel 2001).

In addition, annual fog drip was found to be negatively correlated with annual rainfall (Figure 1), which indicates that fog drip may be of greater ecological importance during the dry years when rainfall is low and fog drip is high. The exact relationship is yet to be verified as we only have four data points. However, this trend is consistent with the empirical observation that higher fog drip and more fog days occurred during a dry year (Liu *et al.* 2007). Fog drip, measured as throughfall in our study, was quantified on days with no rain events, and was not quantified on days with rain events. Therefore, part of the negative correlation is a result of the collection method. But this effect should be very low since radiation fog could not be formed in this region following heavy rain.

During the observation period, fog drip was recorded during heavy fogs only, which accounted for 68% of all the fog events. The remaining light fog events were completely intercepted by the tree foliage before the water could reach the ground. In the cool-dry season, fog drip was recorded

**Table 1** | Seasonal distribution of fog drip, daily fog drip and rainfall in the tropical seasonal rain forest of Xishuangbanna, SW China during 1999–2002. Daily fog drip is the average fog drip per number of fog days with fog drip. Values given are means ± 1SD ($n = 4$)

| Season | Fog drip (mm) | Daily fog drip (mm/d) | Rainfall (mm) | Fog drip/Rainfall (%) |
|---|---|---|---|---|
| Cool-dry | 56.2 ± 5.2 | 0.52 ± 0.17 | 115 ± 34 | 49 |
| Hot-dry | 20.6 ± 4.0 | 0.41 ± 0.18 | 62 ± 18 | 33 |
| Rainy | 12.6 ± 2.4 | 0.22 ± 0.15 | 1531 ± 182 | < 1 |
| Annual | 89.4 ± 13.5 | 0.38 ± 0.27 | 1718 ± 206 | 5 |

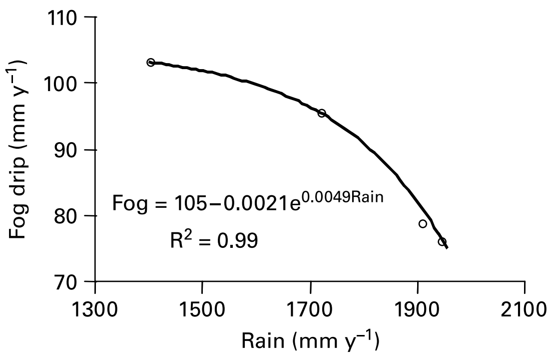


**Figure 1** | The relationship between annual fog drip and rainfall in the tropical seasonal rain forest at Xishuangbanna, SW China during 1999–2002 (adapted from Liu *et al.* 2004).

during 92% of all fog events, while in the rainy season, fog drip was recorded during 36% of all fog events.

The overall mean daily fog drip of 0.38 mm in this study (Table 1) also falls in the lower range reported by previous studies (Bruijnzeel & Proctor 1995). Bruijnzeel (2001) suggested typical cloud water deposition rates (fog drip or fog deposition on collector) are 1–2 mm/d (range 0.2–4.0 mm/d). Huang *et al.* (2001) showed that there is a broad range of droplet sizes in radiation fogs at this site and, frequently, droplet diameters of 8.0–13.6 μm are formed, which is the ideal size for producing fog drip (Grunow 1955). The relatively high liquid water content (0.12–0.25 g/m$^3$; Huang *et al.* 2001) and the typical droplet sizes of fog are not thought to restrict the fog deposition rate at this site. The low fog drip may be partially attributed to the low wind speeds prevailing at our site (<2 m/s). For the low wind speeds which are typical for radiation fog, deposition (or sedimentation) is the dominant process of fog precipitation (Lovett 1984; Glasow & Bott 1999). Furthermore, the method used to collect fog drip water in this study is also different from other studies, which could contribute to the relatively low value because water storage on the canopy and the direct evaporation of fog water from the wet canopy were not included. This storage could be as high as 1.1 mm on a typical day and some of the water could be released at relatively high wind speeds in the tropical seasonal rain forest (Liu *et al.* 2004). As the data obtained from canopy drip are net inputs to the forest floor rather than fog interception, the estimate is considered to be conservative compared to fog interception values obtained from fog gauges.

In this site, fog input to the forest floor over the entire dry season accounted for 86% of the total annual fog drip. For the cool-dry and hot-dry seasons, fog drip represents, on average, up to 49 and 33% of the total rainfall, respectively, while for the rainy season, it is less than 1% (Table 1). As such, fog represents a very important hydrological input for this tropical seasonal rain forest, especially during the hot-dry season when plant demand for water is high. The seasonal trend observed on this site is similar to the pattern reported by Holder (2003) in Guatemala & Vermeulen *et al.* (1997) in the Netherlands, but different from some high-altitude montane cloud forest (Bruijnzeel 2001). We attribute this difference to the mechanism of fog formation in different sites. The clouds in montane cloud forests form close to coasts and are mainly caused by the cooling effect of rising air plus long-wave radiation loss. However, the fog in Xishuangbanna is mainly a result of long-wave radiation at relatively low altitude (750 m). Radiation fog events in this site are generally associated with low wind speeds and region-wide air mass stagnation resulting from strong nighttime radiative cooling (Liu *et al.* 2005*a*).

The mean annual rainfall during the study period was 1718 mm, which was higher than the climate normal (1487 mm). However, this higher annual rainfall was mainly due to the occurrence of several large storms in the rainy season (responsible for 90% of annual rainfall). As such, the higher annual total is not likely to compensate for the increased plant-water shortage during the dry season inferred by Zhang (1986).

## FOG CHEMISTRY

Fog chemistry was measured at the rain forest site between November 2001 and October 2002. Fog water samples were collected on an event basis, by using passive cylindrical string collectors described by Schmitt (1987). Two of these collectors mounted on a 72 m high meteorological tower at 38 m (0.5 m above the canopy) in the study site were used to collect sufficient fog water. Fog drip samples were collected as mentioned in the above section. To reduce the number of samples for chemical analysis, the twelve fog drip samples for each collection period were combined after separate measurement of the volumes collected. The results (Liu 2005; Liu *et al.* 2005*b*) showed

**Table 2** | Volume-weighted mean ion concentrations (μeq/ℓ) with minimum and maximum values along with their pH values in fogwater, fog drip and rainwater in the tropical seasonal rain forest at Xishuangbanna, SW China during 2001–2002. (n.d.: not detectable)

| | Fog water ($n$ = 17) | | | Fog drip ($n$ = 17) | | | Rainwater ($n$ = 9) | | |
|---|---|---|---|---|---|---|---|---|---|
| Ion | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. |
| pH | 6.78 | 5.71 | 7.92 | 7.30 | 6.14 | 8.18 | 6.13 | 5.69 | 7.25 |
| $H^+$ | 0.39 | 0.01 | 2.00 | 0.12 | 0.01 | 0.79 | 0.80 | 0.12 | 2.07 |
| $Cl^-$ | 22.7 | n.d. | 59.4 | 35.4 | 5.8 | 85.1 | 14.5 | n.d. | 55.5 |
| $SO_4^{2-}$ | 27.2 | n.d. | 59.3 | 31.9 | 9.3 | 81.6 | 10.1 | 5.2 | 48.1 |
| $NO_3^-$ | 30.7 | 6.7 | 68.7 | 79.1 | 6.6 | 98.4 | 15.3 | 6.3 | 62.5 |
| $HCO_3^-$ | 85.2 | 22.3 | 172.7 | 149.9 | 26.9 | 192.7 | 37.3 | 16.4 | 79.6 |
| $Na^+$ | 16.8 | 11.9 | 57.4 | 40.7 | 14.1 | 112.6 | 9.3 | 3.6 | 45.2 |
| $K^+$ | 29.7 | 8.2 | 69.8 | 118.2 | 16.3 | 154.3 | 7.5 | 2.1 | 58.2 |
| $Ca^{2+}$ | 66.4 | 9.4 | 107.1 | 97.2 | 12.4 | 136.4 | 28.6 | 4.4 | 113.7 |
| $Mg^{2+}$ | 54.8 | 7.5 | 97.6 | 126.8 | 8.2 | 201.8 | 28.3 | 3.8 | 92.5 |
| $NH_4^+$ | 52.7 | n.d. | 74.2 | 27.2 | n.d. | 59.0 | 23.2 | n.d. | 54.8 |

that the ion concentrations in fog water and rainwater were generally low, and there is great variability in ion concentrations of individual events (Table 2). Compared to rainwater, the fog water shows much higher ion concentrations. The pH of fog water ranged between 5.71 and 7.92, and rainwater between 5.69 and 7.25 indicating an alkaline nature as compared to the reference level of 5.65, which results from the equilibrium of atmospheric $CO_2$ with precipitation (Charlson & Rodhe 1982). Fog water and rainwater were considerably more acidic during the middle of the dry season (January) compared to the early dry season (November) and rainy season ($P < 0.05$). The high pH values of fog water and rainwater in this study site may be attributed to high concentrations of $NH_4^+$, $Ca^{2+}$ and $Mg^{2+}$ compared to low concentrations of $SO_4^{2-}$ and $NO_3^-$.

The fog droplets are not falling on the forest floor but are rather intercepted by leaves in the forest canopy. Additional mineral matter is transferred to the forest floor. The pH and ion concentrations ($Ca^{2+}$, $Mg^{2+}$ and $K^+$) rose significantly from fog water to fog drip in the tropical seasonal rain forest, which could be caused by the washout of the soil– and ash-oriented ions deposited on the leaves and the alkaline ionic emissions by the leaves, since biomass burns are very common in this region. Crutzen & Andreae (1990) also pointed out that biomass burning, particularly in the dry season, can play a major role in tropical atmospheric chemistry, which results in ash deposition on the canopy and subsequent wash-off and solution of ash particles. Although the radiation fog density and deposition fluxes are usually not as high as in clouds advected to high elevation ecosystems, water and chemical substance input associated with radiation fog may be important, especially for regions with a less pronounced orography (Vermeulen *et al.* 1997; Glasow & Bott 1999). Considering the wet deposition transferred by rain, the fog deposition on the forest canopy may not account for a large proportion of the total chemical inputs during the wet season. However, the accumulation of fog deposition due to high frequency and long fog immersion time during the dry season can increase the annual chemical inputs delivered to the rain forest to a great extent (10–25% of the total wet deposition for major ions). It is apparent that fog deposition is a potentially important, but not dominant, source of chemical elements to the tropical rain forest.

## ECOLOGICAL AND PHYSIOLOGICAL IMPLICATIONS

In this tropical seasonal rain forest site, only 10% of the annual rainfall occurs during the dry season (November–April) from relatively few storms. Because the fog drip to the forest floor accounts for 33–49% of the total rainfall during this period, it constitutes an important additional source of moisture to plants. Inputs from fog drip could be critical to tree survival toward the end of the dry season when soil moisture levels are low and daytime air temperature and insolation tends to increase. Oberlander (1956) pointed out that growth of seedlings appeared to be stimulated beneath parent trees which dripped fog. In addition, frequent fog deposition would offset the high interception losses due to the low intensity rainfall and dense canopy, contributing to the water reaching the soil surface (Hutley *et al.* 1997). Moreover, fog can contain critical nutrients, such as nitrogen, which are essential for healthy plant growth and can influence biogeochemical cycles (Weathers & Likens 1997; Dawson 1998).

Variation in the stable oxygen and/or hydrogen isotopic composition of precipitation can be used to identify different water sources which might be used by vegetation (Brunel *et al.* 1995; Dawson 1998). Fog is isotopically enriched in the heavier isotopes relative to rainfall and water in the surface soil layers (Aravena *et al.* 1989; Ingraham & Matthews 1990; Dawson 1998). For shallow rooted species, like most understory species, fog may be the main source of water input during the dry season when deep soil water is unavailable in this forest stand. By examining oxygen isotopic ratios ($\delta^{18}O$) in fog drip, rainwater, shallow soil water, groundwater (Liu *et al.* 2005*a*, 2006), and plant xylem water (Liu 2005) and using a linear two-end-member mixing model (Dawson 1998) during the year of 2003, we calculated the percentage of xylem water ($P_f$) derived from fog drip (Liu 2005). This two-end-member mixing model successfully predicted the proportion of fog and rain water used by plants (Brunel *et al.* 1995; Dawson 1998). The model is as follows: $\delta X_p = \delta_{Xsf} P_f + \delta X_{gw}(1 - P_f)$, where $\delta X_p$ is the isotopic signature of plant xylem water, $\delta X_{sf}$ is the isotopic signature of fog drip and soil water, and $\delta X_{gw}$ is the isotopic signature of groundwater. $\delta X_{sf}$ was determined by combining the fog drip isotope value with the isotope value from the shallow soil water, and dividing this value by 2 (adapted from Dawson 1998). Our preliminary results (Liu 2005) showed that during the sampling days in the dry season, two understory species, *Mananthus patentiflora* and *Dysoxylum binecteriferum*, obtained between 25–79% (mean = 54%) and 12–60% (mean = 32%) of their water from fog drip, respectively. However, the canopy dominant species, *Gironniera subaequalis*, *Pometia tomentosa* and *Ardisia tenera*, obtained only between 5–25% (mean = 11%), 5–27% (mean = 13%), and 6–31% (mean = 15%) of their water from fog drip, respectively. These data may support a hypothesis that the understory vegetation shows greater reliance on fog water than the canopy dominants (Dawson 1998). However, further study is required to confirm this hypothesis since samples for comparison are very limited in our study. Dawson (1998) found that smaller trees and understory species using more fog water than large trees is consistent with rooting depth information since smaller trees possess a greater fraction of shallow roots and may therefore use a greater proportion of shallow soil water which is from fog drip. Previous results also showed that the soil water collected in the dry season appeared to contain more fog drip water than that collected in the rainy season (Liu *et al.* 2005*a*). The groundwater in both seasons had an isotopic composition similar to rainwater, suggesting that fog drip water does not play a significant role as a source of recharge for the groundwater. This groundwater was thought to be recharged solely by rainwater.

Fog water contributes directly to water input, but its effect is also indirect by reducing transpiration and hence plant-water deficit (Burgess & Dawson 2004). It has been suggested that intercepted fog water which remains on foliage may be considered as a net gain, since the energy expended in its evaporation from the leaf surfaces would have been used in transpiration of an equal amount of water from the soil (Kerfoot 1968). Reduction of evapotranspiration through reduction of the number of hours of sunshine and the daytime temperature were also considered important (Bruijnzeel *et al.* 1993). Grubb & Whitmore (1966) stated that the whole aerial environment is altered by foggy conditions, and basic physiological processes of plants are bound to be affected. These features were studied recently by Hutley *et al.* (1997) in an Australian subtropical rainforest, and their results showed that the frequent occurrence of fog and wet canopy results in reduced transpiration rates and direct foliar absorption of moisture alleviates water deficits of the upper crown leaves and branches during the dry season. They also pointed out that fog has indirect effects on the rate of tree photosynthesis and respiration as the aerial environment is greatly altered in terms of vapour pressure deficit, radiation and temperature. Frequent wetting and direct uptake of water by canopy elements may also have consequences for cambial development and could result in complex patterns of xylem development and branch hydraulic resistances, as pointed out by Doley (1970).

Within the tropical rain forest ecosystem in Xishangbanna, fog events and fog drip mainly occur during the dry season when plants remain in leaf and continue to transpire (Liu *et al.* 2004), suggesting that the hydrological and ecological consequences of fog occurrence could be significant. Observations indicated that higher fog drip during dry years implies that fog water is important in sustaining the rain forest vegetation through dry seasons in dry years. As such, fog water should be considered when calculating the water and nutrient balance of the entire catchment areas. These results and those shown here would develop a testable hypothesis that fog plays an important role in the presence of the tropical rain forest in Xishuangbanna. One may argue that the presence of tropical rain forest under atypical climate conditions (drier and colder) in Xishuangbanna was because of the sustained water supply in valleys. Indeed, the tropical rain forest is primarily formed in wet valleys and lowlands. However, it is in the wet valleys and lowlands that heavy radiation fogs frequently occur, which benefit vegetation in the whole forest stand not just streamside trees. Moreover, in the wet valleys and lowlands, the heavy fogs could greatly reduce the decreasing amplitude of air temperature at the night.

## CONCLUSIONS

The tropical rain forest in Xishuangbanna, SW China has a high floristic diversity and is closely related to Malaysian rain forests in flora. This forest would not normally be established in such a climatic region as Xishuangbanna (less precipitation and lower air temperature) compared to those of the lowland moist tropics. It is believed that the frequent occurrence of radiation fog might play an important role in the water relations of plants and in the hydrological cycle of this type of rain forest. However, the multiple hydrological and ecological effects of radiation fog are not well understood.

Despite some information on the hydrological and chemical consequences of fog on the rain forest obtained, it must be admitted that our knowledge remains fragmentary and preliminary on the fog hypothesis. Further detailed studies which cover the entire water cycle, nutrient balance and water use by plants in this ecosystem are warranted. Before a sound understanding can be obtained, reliable information is urgently needed on the effects of fog on transpiration, photosynthesis and respiration rates, as well as on the rooting depth of plants. Such information is lacking at present. In addition, there are no published studies which have combined hydrological process and streamflow dynamics in this forest catchment. Clearly, more detailed research on the fog hypothesis, i.e. fog plays an important role in the presence of the tropical rain forest in Xishuangbanna, is urgently needed.

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