

热带人工橡胶林林冠截留雾水的边缘效应研究

刘文杰^{1, 2, 3, *}, 张一平¹, 李红梅¹, 刘玉洪¹, 段文平¹

(1. 中国科学院西双版纳热带植物园, 云南 勐腊 666303; 2. 中国科学院生态环境研究中心, 北京 100085;
3. 中国科学院研究生院, 北京 100039)

摘要:利用 2001 年 11 月~2002 年 10 月的林缘和林内雾水截留及相关环境因子观测资料,对西双版纳热带人工橡胶林林冠截留雾水的边缘效应进行了研究。西双版纳热带人工橡胶林内的雾日数及雾日频率呈现明显的季节变化,全年雾日数可达 172 d,其中雾季(11~翌年 2 月份)的雾日数及雾日频率最多(高),月均雾日数可达 23 d(76.7%)。由林缘至林内,年雾水截留量在迎风面和背风面均呈现指数形式急剧减小,二者均是在林缘最边行外测的林冠下(0 m 处)达到最大,分别为 41.1 mm 和 24.3 mm。迎风面和背风面林缘 0 m 处的雾水截留量分别是林内雾水截留量(16.2 mm)的 2.5 倍和 1.5 倍。迎风面雾水截留在林内约 25 m 处趋于稳定,而背风面在林内约 15 m 处趋于稳定。林缘处的雾水截留量与日 0:00~10:00 平均风速呈显著的正相关($P<0.01$)。风速大,则雾水截留的边缘效应向林内越深入,且空间变异性减小。相对于迎风面林缘 0 m 处的雾水截留而言,大的风速将削弱林内和林缘雾水截留量的差别,从而导致更多的雾水进入森林。

关键词:截留雾水;林冠;边缘效应;人工橡胶林;西双版纳

Edge effect of intercepted fog water by forest canopy at a rubber plantation in Xishuangbanna, Southwest China

LIU Wen-Jie^{1, 2, 3, *}, ZHANG Yi-Ping¹, LI Hong-Mei¹, LIU Yu-Hong¹, DUAN Wen-Ping¹ (1. Xishuangbanna Tropical Botanical Garden, CAS, Mengla, Yunnan 666303, China; 2. Research Centre for Eco-environmental Sciences, CAS, Beijing 100085, China; 3. Graduate School of CAS, Beijing 100039, China). *Acta Ecologica Sinica*, 2004, 24(7): 1430~1435.

Abstract: Xishuangbanna is located at the northern edge of the distribution of tropical forest in Southeast Asia, and it has a very high frequency of radiation fog, especially during the dry season (November~April). 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. Intercepted fog water by forest canopy from both the windward edge and leeward edge to the interior of the forest and related microclimatic factors were measured during November 2001 and October 2002 at a rubber (*Hevea brasiliensis*) plantation in Xishuangbanna, Southwest China. The object of the study is to determine whether the windward edge and leeward edge of forest floor receives greater deposition of fog water than the interior of the forest. Bottle-funnel collectors were used to determine daily amount of intercepted fog water during fog-only events along windward and leeward transects in the rubber plantation. Related microclimatic variables including air temperature, relative humidity, wind speed, wind direction, and rainfall were also recorded by a meteorological observation system (MAOS-1) mounted on a 31 m meteorological tower in the study stand. The number of fog days was extremely higher inside the rubber plantation, with 172 days per year. The fog frequency was up to 76.7% in the foggy season (November~February). During the study period, an absolute amount of annual intercepted fog water in the rubber plantation was up to 16.2 mm. Annual intercepted fog water varied dramatically and

基金项目:国家自然科学基金资助项目(30100019);云南省应用基础研究基金资助项目(2001C0023Q、2003C0009Z);国家重点基础研究发展计划资助项目(2003CB415100)

收稿日期:2003-10-30; **修订日期:**2004-04-10

作者简介:刘文杰(1969~),男,河南省封丘县人,博士生,副研究员,主要从事热带森林水文和气候研究。E-mail:lwj@xtbg.org.cn

Foundation item: the National Natural Science Foundation of China (No. 30100019), the Foundation for Natural Sciences of Yunnan Province, China (No. 2001C0023Q and 2003C0009Z) and, the National Key Project of Basic Research (No. 2003CB415100).

Received date: 2003-10-30; **Accepted date:** 2004-04-10

Biography: LIU Wen-Jie, Ph. D. candidate, Associate professor, mainly engaged in forestry hydrology and climatology.

decreased exponentially from the windward and leeward edge to the interior of the forest. Intercepted fog water at the edge of the forest was on average 1.5 to 2.5 times, and up to 9 times, greater than that in the interior of the forest. The intercepted fog water “stable-distance”, i. e. the point at which the fog water interception is generally no change within the forest edge farther, was found to be 25 m for the windward edge and, 15 m for the leeward edge. We also found that the intercepted fog water at the edge was positively correlated with average wind speed during 0:00~10:00 of the day ($P<0.01$), demonstrating that high wind speed resulted to further extension of the edge effect and lower spatial heterogeneity. Our intercepted fog water data were compared to other studies, which showed similar result. Although our data are not extensive enough to allow broad generalizations, they provide further evidence that the amount of intercepted fog water from the forest canopy to the forest floor in edge zones can be very different from that in the forest interiors. In regions of high winds and significant intercepted fog water, the edge effect is likely to be even greater than we have shown here. We attribute this difference to the mechanism of fog formation in different sites. The fog in montane forest close to coasts with high wind is mainly caused by the cooling effect of rising air plus long-wave radiation loss. However, the fog in Xishuangbanna, which is far from the coast, is mainly a result of long-wave radiation at relatively low altitude. Meanwhile, it is reasonable to believe that converting multi-layer tropical rain forest with single-layer rubber plantation will reduce intercepted fog water in adjacent tropical rain forest. Furthermore, the method used to collect fog drip water is also different from other studies that could contribute to the relatively low value reported in this study. As the data obtained from canopy drip are net inputs to the forest floor, the estimate is considered to be conservative compared to fog water via impaction by fog gauges. We could further hypothesize that the edge of the rubber plantations would generally intercept less fog drip than that of the tropical rain forest during the dry season. The edge effect phenomenon we have described could have important effects on many ecological processes, biodiversity and forest regeneration. These results also demonstrate the importance of understanding the impacts of climate factors, and have important implications for ecologists and hydrologists interested in fog-inundated ecosystems and the plants that inhabit them.

Key words: intercepted fog water; forest canopy; edge effect; rubber plantation; Xishuangbanna

文章编号:1000-0933(2004)07-1430-06 中图分类号:Q945 文献标识码:A

雾降水(Fog water interception, Occult precipitation and, Horizontal precipitation)一直被认为是一种极其重要的水文和化学输入项,其生态效应是多方面的^[1,2]。雾的形成不仅凝结水汽^[2]、沉降养分^[3]进入森林,同时也释放了凝结潜热而减弱了降温强度^[4],及缩短了日照时数而消减蒸发散,这对缓解植物干旱、补充养分不足、减弱因低温加剧的光抑制等方面具有重要作用^[2]。研究表明,热带山地云雾林(Tropical montane cloud forest)内的雾水沉降可达全年降水量(雨水+雾水)的2.4%~60.6%^[5,6],而雾水中化学离子浓度为雨水中相应离子的2~24倍^[7~10],可提供全年养分输入(雨水+雾水)的8%~30%^[3]。

森林边缘的存在极大地增加了景观的片段化,影响了许多生态过程,对生物多样性和森林更新具有深远的影响^[11,12]。研究表明^[13,14],许多水分、养分和污染物在进入森林生态系统时,主要通过大气传输并以雨、雪、雾等形式的湿沉降和大气颗粒的干沉降形式进行,其中,林缘是清除和浓集这些养分及污染物的最活跃区域。由于雾水沉降极大地受制于风速和植被群落结构^[15],因而,Weathers等^[16]认为森林边缘处的雾水截留具有非常高的空间变异性。

与世界其它热带森林分布区相比,西双版纳热带森林是在水分、热量均不足条件下分布的热带北缘森林群落,由于地处季风气候特点的热带北缘,热带森林受到了季节干旱和冬季低温的影响^[17]。人工引种的巴西热带三叶橡胶树(*Hevea Brasiliensis*),同样也受到了季节干旱和冬季低温的影响,呈现干季的2月底至3月初全部落叶的生态适应特征。本区年降雨量1500~1600 mm,但雾季(11~翌年2月份)和干热季(3~4月份)雨量偏少,不足全年的13%。但本区是有名的静风(年均风速0.5 m/s)、多雾(年雾日>170 d)区,雾季和干热季多有辐射雾出现。尤其是在热带雨林覆盖区,辐射雾更是频繁出现。因而,雾所塑造的温湿环境必然对热带森林的生存和发展起到一定的作用。刘文杰等^[18]对本区热带人工橡胶林林冠截留雾水的研究表明,全年雾水截留量达18.6 mm(雾季占91.9%)。然而,有关热带森林林缘处雾水截留的空间变异性研究并未涉及。本文利用2001年11月至2002年10月在热带人工橡胶林林缘和林内观测的雾水截留和环境因子的资料,研究橡胶林林冠截留雾水的边缘效应,为热带森林的雾水水文和化学效应及水分和养分循环规律的深入研究提供参考。

1 样地自然环境及群落特征

观测点位于勐海县勐腊镇勐腊热带系统研究网络(CERN)西双版纳热带人工橡胶林辅助观测样地(21°55'39" N, 101°15'55"E,面积约0.8 km²,平均海拔600 m)内,样地为平均坡度约10°的西南向坡地。本区属热带北缘西南季风气候控制,一年中有干季(包括雾

季(11~翌年2月份)、干热季(3~4月份)、雨季(5~10月份)之分^[19]。年均气温21.7℃,年均风速0.7 m/s,相对湿度86%,年降雨量1400~1500 mm,其中雨季占83%~87%,干季占13%~17%。

热带人工橡胶林观测样地群落高22 m左右,上层乔木为三叶橡胶树(*Hevea brasiliensis*),株行距为2 m(5 m,下层为木奶果(*Baccaurea ramiflora*)、萝芙木(*Raurol vomitoria*)两个小乔木组成,间种在橡胶树行间。该群落为定植30余年的人工林,上下层植物相间排列种植,株行距规范、林相整齐^[20]。

2 研究方法

在人工橡胶林林缘迎风方向(SW,盛行风方向)和对应的背风方向(NE),由林缘至林内30 m每5 m间距水平各安置1个口径0.8 m的圆形漏斗承接林冠截留后滴落的雾水(漏斗接水面距地表0.5 m)。参考Weathers等的研究方法^[16],林缘边界(即0 m处)选择在橡胶树边缘行的外测距树干2.5 m处,即约林冠外测的垂直投影点。同时,林内又随机安置4个漏斗测定林内截留雾水。各漏斗出水口处悬挂1000ml的塑料瓶承接雾水,塑料瓶内503ml水换算到单位面积上等于1 mm的截留雾水。每日9:00左右(林冠无雾水滴落时)观测雾水量(观测自2001年11月至2002年10月)。如夜间有降雨发生,则次日的截留雾水量视为0。这种方法或许会过低估计雾水截留量,但在西双版纳地区,辐射雾的发生多是在晴朗而无云、雨的夜空下,地表的强烈长波辐射降温所致,因而,这种方法是可行的^[21]。同时,由于林冠截留的雾水并未导致树干茎流,因而没有进行树干茎流的观测。

将MAOS-1全自动小气候观测系统(包括4套温度、湿度、风速传感器及一台风向传感器和雨量计等,长春气象仪器研究所生产)安置在人工橡胶林定位样地小气候梯度观测铁塔上(塔高31m),观测环境小气候要素的变化特征。在最上林冠层(高22 m)以上0.5 m布设1套温、湿、风传感器,其余3套分别安置在距地表1.5 m、9 m及铁塔顶部,风向传感器和雨量计则安置在铁塔顶部分别测定风向和大气降雨(采集频度均为1次/h,1997年11月开始,至今一直观测)。雾日采用人工观测,雾日定义为水平能见度<1 km及至少持续15min^[7]。

3 结果

3.1 雾日的年变化

在热带人工橡胶林内,雾日数及雾日频率呈现明显的季节变化(表1)。雾季(11~翌年2月份),橡胶林内雾日数及雾日频率最多(高),月均雾日数可达23 d(76.7%),比干热季(3~4月份)的相应多10 d,比雨季(5~10月份)多14 d。橡胶林内全年雾日数可达172 d。橡胶林内雾日的这种季节变化与各季的降雨量呈明显的负相关^[18]。在本地区,降雨多,则阴雨天气多,而阴雨天不利于辐射雾的形成,因而雾日少,反之亦然。橡胶林内全年雾日数的季节分布特点,无疑是本地区气候、地形和植被状况的综合反映。雾季和干热季,西南季风退缩,本区高层大气受西风带南支西风急流控制^[19],因独特的地形条件作用,低层大气稳定、干燥,云量稀少,夜间辐射雾可频繁出现,且雾生成和消散时间较稳定、雾层厚、范围广;雨季,西南暖湿气流为本区带来了充沛的雨水,云量和雨日均多,因而雾日少。但在雨季晴朗少云的夜间,因空气湿度大,地表的长波辐射降温也极易导致辐射雾的形成,但雾层较薄、范围较小。雾季和干热季,辐射雾通常在夜间23:00~00:00形成,可持续到次日11:00左右,且辐射雾在雾季的1月份呈现最为浓重;雨季,雾的生成和消散时间分别为1:00~2:00和8:00~9:00^[21]。

3.2 雾水截留的边缘效应

3.2.1 迎风面和背风面林缘处的雾水截留 表2为人工橡胶林迎风面和背风面由林缘至林内各测点的年雾水截留量。由表2可看出,由林缘至林内,林冠截留的雾水在迎风面和背风面均急剧减小,二者均是在林缘最边行外测的林冠下(0 m处)达到最大,分别为41.1 mm和24.3 mm,前者为后者的1.7倍,即:迎风面林缘处截留的雾水明显大于背风面的相应值。林内的雾水截留量为16.2 mm,与迎风面和背风面由林缘至林内雾水截留趋于稳定的值相近。对迎风面和背风面而言,二者林缘0 m处的雾水截留量分别是林内雾水截留量的2.5倍和1.5倍。

如果迎风面和背风面林缘0 m处的雾水截留量为1(但二者实际数值不同),则林缘附近各测点的相对雾水截留量变化如图1所示。由图1可看出,迎风面和背风面林缘附近的雾水截留变化并不相同,前者的减弱程度明显大于后者。对迎风面而言,雾水截留在林内约25 m处趋于平稳。而背风面在林内约15 m处趋于平稳。

3.2.2 风速对林缘雾水截留的影响 由于雾水沉降极大地受制于风速和植被群落结构^[15],因此,对同一地点、同一植被群落而言,风速越大,则随风携带的雾滴被林冠截留的量将越多^[2]。图2为雾季1月份橡胶林迎风面林缘0 m处的日雾水截留量

表1 人工橡胶林内各季节月平均雾日数(d)和雾日频率(%) (2001-11~2002-10)

Table 1 Monthly average fog events and frequency in different season at rubber plantation during November 2001 and October 2002

项目 Items	雾季 Foggy season	干热季 Hot-dry season	雨季 Rainy season	全年 Whole year
雾日数 Fog events(d)	23	13	9	172
雾日频率 Frequency (%)	76.7	43.3	30.0	47.1

* 雾季(11~翌年2月份) Foggy season (November ~ February); 干热季(3~4月份) Hot-dry season (March ~ April); 雨季(5~10月份) Rainy season (March ~ October)

与日 0:00~10:00 平均风速的关系,如图所示,二者呈现显著的正相关($P<0.01$),即:大的风速与多的林缘截留雾水相对应。

表 2 人工橡胶林迎风面和背风面林缘处的年雾水截留量(mm)由林缘至林内的距离变化(2001-11~2002-10)

Table 2 Annual fog water interception (mm) at the forest edge as a function of distance from the windward edge and leeward edge of the rubber plantation during November 2001 and October 2002

方位 Orientation	距林缘距离 Distance from edge (m)							林内 Interior
	0	5	10	15	20	25	30	
迎风边缘 Windward edge	41.1	31.6	23.8	17.6	17.2	16.0	16.1	16.2
背风边缘 Leeward edge	24.3	20.2	16.6	15.9	16.0	16.1	15.9	16.2

图 3 为雾季 1 月份橡胶林迎风面林缘处的雾水截留在平均风速 $V\geq 1\text{ m/s}$ 和 $V<1\text{ m/s}$ 时由林缘至林内的变化,图中仍采用相对数值。可看出,在两种风速条件下,林缘处雾水截留的变化趋势差别非常大。 $V\geq 1\text{ m/s}$ 时,雾水截留趋于稳定的位置在林内约 20~25 m 处; $V<1\text{ m/s}$ 时,雾水截留趋于稳定的位置在林内约 15~20 m 处,即:风速大,则雾水截留的边缘效应向林内越深入,且空间变异性减小。在两种风速条件下,林缘 0 m 处的雾水截留量分别是林内雾水截留量的 2.5 倍($V\geq 1\text{ m/s}$ 时)和 5 倍($V<1\text{ m/s}$ 时)。这说明,相对于迎风面林缘 0 m 处的雾水截留而言,大的风速将削弱林内和林缘雾水截留量的差别,从而导致更多的雾水进入森林。同时,由图 3 还可看出,迎风面林缘处测点的雾水截留标准差大于背风面林缘测点的相应值,说明风速大时,迎风面林缘处的雾水截留量的不确定性变大。

4 讨论和结论

4.1 讨论

控制林冠截留雾水量多少的因子有风速、可用于截留雾水的植被叶面积、林冠的空气动力学特征、雾的频度和浓度等^[16]。林缘相对于林内具有更多的叶表面暴露于浓雾中,且林缘处风速大于林内,因而林缘处的雾水截留量应该多于林内^[15,16]。西双版纳热带人工橡胶林林缘处的雾水截留平均为林内的 1.5~2.5 倍,这与 Weathers 等^[16]在美国纽约州东南部 Catskill 山的红杉(*Picea rubens* Sarg.)林林缘处测得的结果(平均为 3 倍)相近。他们通过 15 次林冠截留雾水的观测发现,迎风面林缘处的雾水截留量明显高于背风面林缘处,而且由林缘至林内的雾水截留量均迅速递减,本文观测结果同样证实了这一现象。与 Potts^[22]的观测结果相似,Weathers 等^[16]也发现在林缘至林内的某一处(约 10 m 处)林冠截留的雾水最少。Weathers 等认为,这可能是由于林缘处林下的垂直和水平扰动引起林缘内某一处的雾水沉降量显著减弱所致。然而,观测并未发现此种现象,这可能与观测样地的株行距规范、林相整齐和本地区风速较弱(年均风速 0.7 m/s)有关。

对橡胶林迎风面林缘处的雾水截留的观测发现,林缘 0 m 处的平均雾水截留量是林内雾水截留量的 5 倍($V<1\text{ m/s}$ 时),最大可达 9 倍(2002 年 1 月 19 日)。同样,Weathers 等^[16]的观测也发现,迎风面林缘 0 m 处的雾水截留最大可为林内的 15 倍。然而,Weathers 等^[14]对纽约州 Hudson 山谷的另一处湿地山毛榉(*Fagus grandifolia*)林的观测发现,尽管各月间的林缘或林内雾水截留量有显著差别,林缘和林内之间的总雾水截留量却没有显著差异。这可能与他们对山毛榉林下植被的人为全部清除有关,因为林下植被的清除,将导致截留雾水的植被叶面积、林冠和林下的空气动力学特征的极大改变。

与 Weathers^[16]观测的直线减弱趋势不同,西双版纳人工橡胶林林缘至林内的雾水截留量呈指数趋势减弱(图 2,图 3),这可能与本地区风速较弱有关。图 3 也显示出,风速较弱时($V<1\text{ m/s}$),这种指数趋势变得更为明显。西双版纳人工橡胶林林

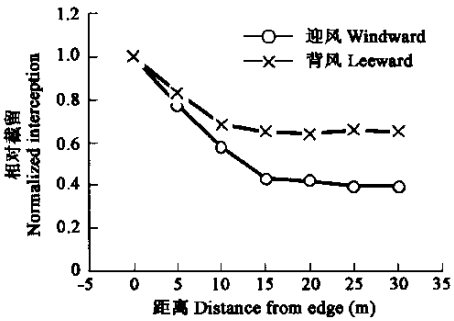


图 1 人工橡胶林迎风面和背风面林缘处的相对雾水截留由林缘至林内的距离变化(2001-11~2002-10)

Fig. 1 Annual fog water interception normalized to interception at the forest edge as a function of distance from the windward edge and leeward edge of the rubber plantation during November 2001 and October 2002

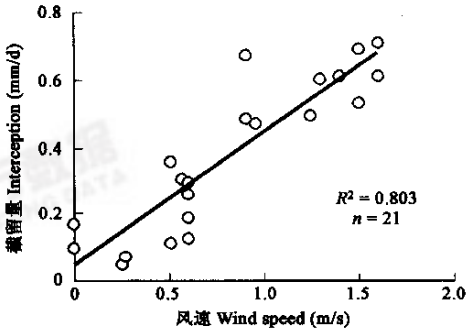


图 2 人工橡胶林迎风面林缘处的日雾水截留量与日 0:00~10:00 平均风速的关系(2002 年 1 月)

Fig. 2 Relationship between fog water interception and average wind speed during 0:00~10:00 of the day at the windward edge for the rubber plantation during January 2002

冠截留的雾水在林缘 15~25 m 处趋于稳定,而 Weathers 等^[16]的观测结果和以及他们对 Hasselrot 等^[23]和 Potts^[22]观测数据的分析表明,林缘内平均 24 m 处的雾水截留量才达到林缘 0 m 处的 50%,尽管文献内没有给出林缘处雾水截留趋于稳定的具体深度。这种区别可能仍然与本区风速较弱有关,风速较弱显然不利于风携带雾滴向林内的进一步渗透。图 3 表明,风速大时,雾水截留的边缘效应向林内更深入,且空间变异性减小。

在人工橡胶林收集的雾水实际上包括了露水。根据本文作者的研究^[4],雾是在露形成后,空气湿度接近饱和时才出现,有雾必有露,但有露并不一定有雾形成;仅有露形成的天气里,林冠叶片被浸湿,但没有形成由叶片滴落的露水;因此,本文的林冠截留雾水实际上是在叶片被露水浸湿后,林冠进一步对雾的机械拦截作用所致。与 Weathers 等^[14, 16]、Hasselrot 等^[23]和 Potts^[22]的观测方法相比,本研究采用的大口径漏斗承接滴落的雾水,显然更具有代表性。因为大口径漏斗无疑削弱了短距离滴落雾水的空间差异,从而较真实的呈现出截留雾水的边缘效应。而使用较小口径的漏斗承接雾水,漏斗的摆放位置将极大的影响观测数据的代表性,因为林冠截留雾水的“关键滴落位置点^[24]”会极大的干扰漏斗位置的代表性。因此,Bruijnzeel 等^[24]建议,在使用小口径收集装置收集林冠滴落时,采用移动观测方法更具有说服力。

在研究林缘附近的截留雾水时,无疑各观测点林冠处的风速是必须考虑的重要环境因子,但受观测条件的限制,仅参考了林内观测铁塔上林冠处的风速。显然,风速大时,林缘处的林冠对风的削弱也将增强,从而可能导致更多的雾水被林缘截获。因此,林缘附近截流的雾水与各测点风速、叶面积指数等因子的关系有待进一步研究。

虽然没有测定林缘处雾水截留导致的化学元素和大气污染物干沉降的输入,但 Weathers 等^[14, 16]、Hasselrot 等^[23]和 Potts^[22]的观测数据表明,林缘处沉降的雾水内的化学元素和大气污染物明显高于林内,其沉降速率平均可达林内的 4 倍,林缘处呈现与雾水截留量相似的空间变异性。许多学者的研究还表明^[11, 12, 25],林缘的存在还影响了众多生态过程,可导致林缘许多生物学特性的改变,如林缘附近凋落物分解加快、先锋植物成分的增多、植物对水的需求量增多等,对生物多样性和森林更新也具有非常深远的影响。

林缘截获和浓集更多的水分、养分和大气污染物可能是一种普遍现象,且风速大的地区,这种截获和浓集将会更大^[14]。对本地区而言,人工橡胶林内的年雾水截留量(16.2 mm)远低于本地区热带雨林内的相应值(89.4 mm)^[21],因而,热带雨林林缘处的雾水截留量可能更多。这也说明,热带雨林的水分循环利用和涵养水源功效是人工橡胶林无法比拟的。人工橡胶林在干季 2~3 月份间的全部落叶,无疑是其受水分胁迫的真实写照。对本地区热带森林而言,雨水较少的年份,雾水截留则较多^[21],较多的截留雾水似乎是对雨水不足的一种补充,这可能对热带森林内植物的正常生长具有更为重要的意义。另一方面,本区雾季和干热季的降雨多为短时雷阵雨,对植物利用来说,其有效性无疑远低于缓慢滴落到林下土壤内的雾水。同时,雾季和干热季的白天持续到 11:00 左右的浓雾,极大的缩短了日照时数,因而也相对减少了森林的蒸发散量。

4.2 结论

西双版纳热带人工橡胶林内的雾日数及雾日频率呈现明显的季节变化,全年雾日数可达 172 d,其中雾季(11~翌年 2 月份)的雾日数及雾日频率最多(高),月均雾日数可达 23 d(76.7%)。由橡胶林林缘至林内,年雾水截留量在迎风面和背风面均呈现指数形式急剧减小,二者均是在林缘最边行外测的林冠下(0 m 处)达到最大,分别为 41.1 mm 和 24.3 mm。迎风面和背风面林缘 0 m 处的雾水截留量分别是林内雾水截留量(16.2 mm)的 2.5 倍和 1.5 倍。迎风面的雾水截留在林内约 25 m 处趋于稳定,而背风面在林内约 15 m 处趋于稳定。林缘处的雾水截留量与日 0:00~10:00 平均风速呈显著的正相关关系。风速大,则雾水截留的边缘效应向林内越深入,且空间变异性减小。相对于迎风面林缘 0 m 处的雾水截留而言,大的风速将削弱林内和林缘雾水截留量的差别,从而导致更多的雾水进入森林。

References:

[1] Dallard B, North M H, Harve M J. Pollutant transfer in upland regions by occult precipitation. *Nature*, 1983, **302**: 241~243.
[2] Ingraham N L, Matthews R A. Fog drip as a source of groundwater recharge in Northern Kenya. *Water Resource Research*, 1988, **24**:

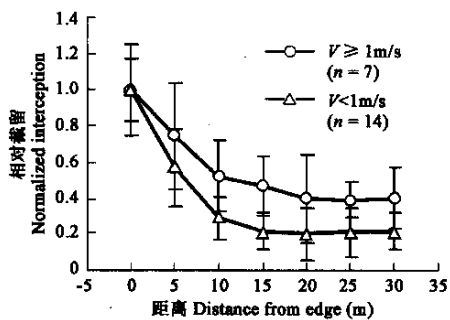


图3 人工橡胶林迎风面林缘处的相对雾水截留由林缘至林内的距离变化(2002年1月)

Fig. 3 Fog water interception normalized to interception at the forest edge as a function of distance from the windward edge of the rubber plantation during January 2002

V 0:00~10:00 平均风速 Average wind speed during 0:00~10:00 of the day; 误差线表示标准离差 Error bars represent standard deviation

of the day; 误差线表示标准离差 Error bars represent standard deviation

1406~1410.

[3] Weathers K C, Likens G E. Clouds in Southern Chile: an important source of nitrogen to nitrogen-limited ecosystems. *Environmental Science and Technology*, 1997, **31**: 210~213.

[4] Liu W J, Zhang K Y, Zhang G M, *et al.* The microclimate of dew and fog formation on canopy layer in the dry season in Xishuangbanna tropical rain forest. *Acta Ecologica Sinica*, 2001, **21**: 165~170.

[5] Cavelier J, Goldstein G. Mist and fog interception in elfin cloud forest in Colombia and Venezuela. *Journal of Tropical Ecology*, 1989, **5**: 309~322.

[6] Cavelier J, Solis D, Jaramillo M A. Fog interception in montane forest across the Central Cordillera of Panama. *Journal of Tropical Ecology*, 1996, **12**: 357~369.

[7] Gordon C A, Herrera R, Hutchinson T C. Studies of fog events at two cloud forests near Caracas, Venezuela II. Chemistry of fog *Atmospheric Environment*, 1994, **28**: 323~337.

[8] Clark K L, Nadkarni N M, Schaefer D, *et al.* Cloud water and precipitation chemistry in a tropical montane forest, Monteverde, Costa Rica. *Atmospheric Environment*, 1998, **32**: 1595~1603.

[9] Gordon C A, Herrera R, Hutchinson T C. Studies of fog events at two cloud forests near Caracas, Venezuela I. frequency and duration of fog. *Atmospheric Environment*, 1994, **28**: 317~322.

[10] Weathers K C, Likens G E. Cloud water chemistry from ten sites in North America. *Environmental Science and Technology*, 1988, **22**: 1018~1026.

[11] Weathers K C, Lovett G M, Likens G E, *et al.* The effect of landscape features on deposition to Hunter Mountain, Catskill Mountains, New York. *Ecological Applications*, 2000, **10**: 528~540.

[12] Cadenasso M L, Pickett T A. Linking forest edge structure to edge function: mediation of herbivore damage. *Journal of Ecology*, 2000, **88**: 31~44.

[13] Lovett G M. Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective. *Ecological Applications*, 1994, **4**: 528~540.

[14] Weathers K C, Cadenasso M L, Pickett T A. Forest edge as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. *Conservation Biology*, 2001, **15**: 1506~1514.

[15] Lovett G M. Rates and mechanisms of cloud water deposition to a subalpine balsam fir forest. *Atmospheric Environment*, 1984, **18**: 361~371.

[16] Weathers K C, Lovett G M, Likens G E. Cloud deposition to a spruce forest edge. *Atmospheric Environment*, 1995, **29**: 665~672.

[17] Zhu H. Research of community ecology on *Shorea chinensis* forest in Xishuangbanna. *Acta Botanica Yunnanica*, 1992, **15**: 34~46.

[18] Liu W J, Zhang Y P, Liu Y H, *et al.* Comparison of fog interception at a tropical seasonal rain forest and a rubber plantation in Xishuangbanna, Southwest China. *Acta Ecologica Sinica*, 2003, **23**: 2379~2386.

[19] Zhang K Y. An analysis on the characteristics and forming factors of climates in the south part of Yunnan. *Acta Meteorologica Sinica*, 1963, **33**: 210~230.

[20] Ren Y H, Cao M, Tang J W, *et al.* A comparative study on litterfall dynamics in a seasonal rain forest and a rubber plantation in Xishuangbanna, SW China. *Acta Phytocologica Sinica*, 1999, **23**: 418~425.

[21] Liu W J, Meng F R, Zhang Y P, *et al.* Water input from fog drip in the tropical seasonal rain forest of Xishuangbanna, Southwest China. *Journal of Tropical Ecology*, 2004, **20**(5).

[22] Potts M J. The pattern of deposition of airborne salt of marine origin under a forest canopy. *Plant Soil*, 1978, **50**: 233~236.

[23] Hasselrot B, Grennfelt P. Deposition of air pollutants in a wind-exposed forest edge. *Water, Air, and Soil Pollution*, 1987, **34**: 135~143.

[24] Bruijnzeel L A, Proctor J. Hydrology and biogeochemistry of tropical montane cloud forests: what do we really know? Pp. In: Hamilton L S, Juvik J O, *et al.* eds. *Tropical montane cloud forests. Ecological studies* 110. New York: Springer-Verlag, 1995. 25~46.

[25] Chen J Q, Franklin F J, Spies T A. Contrasting microclimates among clear-cut, edge, and interior of old growth Douglas-fir forest. *Agricultural and Forest Meteorology*, 1993, **63**: 219~237.

参考文献:

[4] 刘文杰,张克映,张光明,等. 西双版纳热带雨林干热季林冠层雾露形成的小气候特征研究. *生态学报*, 2001, **21**: 165~170.

[17] 朱华. 西双版纳望天树林群落生态研究. *云南植物研究*, 1992, **15**: 34~46.

[18] 刘文杰,张一平,刘玉洪,等. 热带季节雨林和人工橡胶林林冠截留雾水的比较研究. *生态学报*, 2003, **23**: 2379~2386.

[19] 张克映. 滇南气候特征及其形成因子的初步分析. *气象学报*, 1963, **33**: 210~230.

[20] 任泳红,曹敬,潘建雄,等. 西双版纳季节雨林与橡胶多层林凋落物动态的比较研究. *植物生态学报*, 1999, **23**: 418~425.