Canopy Structure Dynamics of Daming Mountain Evergreen Broad-Leaved Forest After the 2008 Extreme Ice Disaster (Post-Print)

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Date: 2017-03-08T00:00:00+00:00

Abstract

Canopy structure is a critical parameter for investigating numerous key ecological functions and processes in forest ecosystems. Evergreen broad-leaved forests represent a typical forest type in subtropical regions, yet research on their canopy structure and dynamics remains limited. In the mid-montane region of Damingshan, Guangxi, we selected a representative slope measuring 200 m in horizontal length and 160 m in width. Across this slope, we established 80 sample plots of 20 m × 20 m, which were evenly divided into 5 slope sections, each containing 16 contiguous plots. During the growing seasons from 2009 to 2012, we measured canopy height (CH), canopy volume (CV), canopy cover (CC), ratio of upper to lower canopy cover (HLr), and canopy leaf area index (LAI), and analyzed the slope position and interannual dynamics of each canopy structural parameter, thereby revealing the canopy structural characteristics and short-term dynamic patterns of subtropical evergreen broad-leaved forests. The results demonstrate that the general features of canopy structure in Damingshan evergreen broad-leaved forest are: mean CH (12.09\$±0.05)*m, meanCV*(2642.51±278.33)*m*^{3}\$ (per 400 m^2 plot), mean CC (59.90\$±3.29)±0.23, *andmeanLAI*2.00±\$0.06. The canopy structure exhibited multilayered characteristics, with mean upper canopy cover of 42.20%, middle canopy cover of 30.35%, and lower canopy cover of 18.05%. Significant variation in canopy structure occurred across slope positions and between years. The coefficient of variation across the slope was: CV (29.84%-55.89%) > HLr (32.90%-53.52%) > LAI (22.48%-43.89%) > CC (16.61%-25.74%) > CH (8.26%-12.77%). The interannual coefficient of variation was: HLr (47.33%-57.00%) > CV (39.70%-49.06%) > LAI (21.58%-48.13%) > CC (20.35%-24.15%) > CH (9.19%-12.59%), indicating that CH maintained relatively strong stability. Canopy LAI displayed a significant slope-scale effect, increasing by 0.34 for every 100 m downslope. Slope position had significant (P=0.022) and highly significant (P<0.001) effects on CH and HLr, respectively. Year had a significant effect on HLr (P=0.013) and highly significant effects on CV and CC (P<0.001). The interaction between slope position and year was significant for CV and LAI (P=0.016, P=0.017). Regression analysis revealed a highly significant linear relationship between crown area and tree diameter at breast height. These findings indicate that Damingshan evergreen broad-leaved forest exhibits relatively low canopy height, small canopy volume, modest canopy cover, and small upper/lower canopy cover ratio and leaf area index, which is associated with the high elevation (934-1223 m) of the study area, shallow soil layers (30-45 cm), and frequent freezing disasters (particularly the extreme freezing disaster of 2008), representing the outcome of long-term adaptation of montane evergreen broad-leaved forest canopy structure to montane environmental conditions.

Full Text

Short-term Dynamics of Canopy Structure in Evergreen Broadleaved Forest after a Freezing Disaster in 2008 in Daming Mountain, Southern China

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Abstract

Canopy structure and dynamics are critical components in the functioning and key ecological processes of forest ecosystems. Evergreen broadleaved forests are the representative community type in the subtropics, but the characteristics of canopy structure in this forest type are poorly understood. In the present study, 80 permanent plots (20 m × 20 m for each plot) on a typical slope (200 m × 160 m) in the mid-mountain region of Daming Mountain were established and equally divided into 5 groups on the slope (16 continuous plots on each slope segment). In order to reveal the features and short-term regulation of the canopy structure in this evergreen broadleaved forest, we investigated and analyzed the slope effects and annual dynamics of canopy structure indexes, including canopy height (CH), canopy volume (CV), canopy cover (CC), ratio of high to low cover (HLr) and leaf area index (LAI) during the growing seasons from 2009 to 2012.

Mean CH, CV, CC, HLr, and LAI of this evergreen broadleaved forest averaged (12.09\$±0.05)*m*, (2642.51±278.33)*m*^{3}\$ (in each plot), (59.90\$±3.29)±0.23, *and*2.00±\$0.06, respectively. The canopy structure was multilayered with CC averaging 42.20% in the upper layer, 30.35% in the middle layer, and 18.05% in the lower layers. Meanwhile, the canopy structure showed differences between slopes and growth years. For different slopes, the coefficient of variation of the index ranked as follows: CV (29.84%–55.89%) > HLr (32.90%–53.52%) > LAI (22.48%–43.89%) > CC (16.61%–25.74%) > CH (8.26%–12.77%). For different growth years, the coefficient of variation of the index ranked as HLr (47.33%–57.00%) > CV (39.70%–49.06%) > LAI (21.58%–48.13%) > CC (20.35%–24.15%) > CH (9.19%–12.59%), showing that CH had relatively strong stability.

We found significant effects of slope scale on LAI with an elevation of 0.34 when sliding down 100 m in the downslope direction. The results of two-way ANOVAs showed that slope position had significant and extremely significant effects on CH ($P = 0.022$) and HLr ($P < 0.001$), respectively, while year of growth had significant effects on HLr ($P = 0.013$) and extremely significant effects on CV and CC (both $P < 0.001$). The interaction effects of slope × year on CV and LAI were significant ($P = 0.016$ and $P = 0.017$, respectively). Correlation analysis showed that there was extremely significant positive correlation between DBH and canopy area. Our results indicated that the canopy structure of evergreen broadleaved forests on Daming Mountain have the characteristics of relatively lower CH, CC, HLr, and LAI, and smaller CV. This could be attributed to the relatively higher elevation (934–1223 m), shallow soil (30–45 cm), and the frequency of freezing disturbances, especially the severe ice storm damage in 2008 on Daming Mountain. This could also be the result of the long-term adaptation of canopy structure in montane evergreen broadleaved forest to environmental conditions.

Keywords: evergreen broadleaved forest; leaf area index; canopy cover; canopy volume; ratio of high to low cover; dynamics

1. Introduction

The forest canopy refers to the sum of all leaves above the forest floor, various epiphytes, and their dead residues [1-4]. Canopy elements, canopy cover (CC), canopy volume (CV), canopy height (CH), ratio of high to low cover (HLr), and leaf area index (LAI) are all important parameters of canopy structure [5-7]. The spatial heterogeneity and vertical stratification of the canopy make it one of the least known habitats containing global terrestrial biodiversity [8-9], often referred to as "the last biological frontier" [4,17]. Canopy structure and its changes directly control the exchange of matter and energy between forest ecosystems and the atmosphere, are closely related to forest microclimate and nutrient cycling [10-14], and have become important components of forest ecosystem functions and key ecological processes [6-7], exerting significant influences on forest regeneration, biological productivity, carbon sequestration, and global climate change [1,15-16].

Research on canopy structure characteristics and dynamics has mainly focused on even-aged forests and plantations in tropical and temperate regions [19-24], with most studies examining simple comparisons of a few indicators such as seasonal changes in parameters [20-24] and differences in site characteristics like slope aspect and position [24-26]. Following the catastrophic freezing disaster of 2008, research on forest canopy damage has increased significantly [27-28]. Recently, some scholars have studied the slope scale effects of canopy layers in a *Larix principis-rupprechtii* plantation on the southern slope of Liupan Mountain [19], but research on canopy structure and dynamics in evergreen broadleaved forests after disasters remains very limited [29-30], particularly lacking studies on the dynamic changes of canopy structure over larger slope areas in primary climax forests [29].

This study takes the primary evergreen broadleaved forest in the Daming Mountain National Nature Reserve as the research object and conducts continuous monitoring of the canopy structure and dynamics of the evergreen broadleaved forest after the 2008 catastrophic freezing disaster, aiming to: (1) deepen understanding of canopy structure dynamic changes in subtropical montane evergreen broadleaved forests, (2) provide basic data for simulating carbon, water, and flux aspects at stand, landscape, and regional scales in this region, and (3) enrich canopy science theory.

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2. Study Area

Daming Mountain National Nature Reserve (23°10 –23°38 N, 108°18 –108°45 E) is located in central-southern Guangxi and belongs to the south subtropical monsoon climate zone. The Tropic of Cancer runs through its central region, creating a unique geographical location that preserves relatively intact primary forests. The area has complex and diverse ecological environments that have nurtured rich biodiversity, making Daming Mountain an important species gene bank in the surrounding region with 2,047 species of vascular plants [32], forming an important barrier for regional ecological security [33].

The climate features a mean temperature of 15.1°C in July, 21.9°C in January, with extreme high temperatures of 28.6°C and extreme lows of -6.0°C. The average annual precipitation is 2,630 mm.

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3. Methods

3.1 Plot Construction A long-term monitoring plot of 3.2 hm^2 was established in the evergreen broadleaved forest on Daming Mountain at an elevation of 934–1223 m, with a slope gradient of 30–35°. The plot measured 200 m × 160 m and was divided into 80 sample plots of 20 m × 20 m using a total station. Each sample plot was marked with permanent aluminum tags and labeled with plot numbers and corresponding coordinates. The plot was divided from bottom to top into 5 continuous slope positions (each slope position included 16 continuous 20 m × 20 m sample plots).

The dominant species in the survey area were *Huodendron biaristatum* (37.1% of importance value), *Acer fabri* (17.2$±12.3), ∗*Stewartiagemmata* ∗ (20.6±11.2), ∗*Diospyrosmorrisiana*∗(18.5±16.6), ∗*Engelhardtiaroxburghiana*∗, ∗*Litseasuberosa*∗ (9.2±9.3), *and* ∗ *Machiluspauhoi* ∗ (9.0±$8.8).

3.2 Canopy Survey Based on the established plots, all woody plants with DBH ≥ 1.0 cm in each 5 m × 5 m subplot were tagged with aluminum plates, recording tree numbers, DBH, height, crown width, and other information. Canopy images were collected at the center position of each 20 m × 20 m sample plot using a CI-110 digital plant canopy imager (CID Inc., Camas, Washington, USA) during the growing season from 2009 to 2012. The observation time for each sample plot was 25-30 days.

3.3 Data Processing and Statistical Analysis The illustration of forest canopy structure in Daming Mountain evergreen broadleaved forest is shown in [Figure 1: see original paper]. Trees in each sample plot were divided into upper (>8 m), middle (4-8 m), and lower (0-4 m) layers by tree height. CH was represented by the average height of the tallest trees in each sample plot. CV was represented by the sum of tree crown volumes of all trees in each sample plot, with tree crown volume calculated using the cylinder formula. CC was the percentage of vertical projection of all tree crowns in the sample plot area. HLr was the ratio of upper to lower canopy cover. LAI was calculated by analyzing canopy images using the built-in canopy analysis software of the canopy analyzer.

One-way ANOVA was used to test the significance of differences in CH, CV, CC, HLr, and LAI among survey years. Two-way ANOVAs were used to analyze the effects of slope position, survey time, and their interactions on CH, CV, CC, HLr, and LAI. Multiple comparisons were performed using the LSD method. All data were processed and statistically analyzed using SPSS 20.0 software, with significance level set at $P < 0.05$. Data plotting was performed using SigmaPlot.

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4. Results

4.1 Canopy Height and Volume Dynamics The canopy height (CH) of Daming Mountain evergreen broadleaved forest averaged 12.09 m, with values ranging from 12.00 to 12.21 m during 2009-2012, showing a weak increasing trend overall. CH differed significantly among different slope positions ($P = 0.022$), with the upper slope being significantly higher than the middle slope.

Year had no significant effect (P = 0.656), and the interaction between slope position and year was not significant (P = 0.964).

The canopy volume (CV) of Daming Mountain evergreen broadleaved forest at different slope positions ranged from 2173.57 to 3283.90 m^3 during 2009-2012, with a mean value of 2624.51 m^3. Year had an extremely significant effect on CV ($P < 0.001$), with CV in 2011 and 2012 being significantly higher than in 2009 and 2010. Slope position had no significant effect (P = 0.103), but the interaction between slope position and year was significant (P = 0.016). In 2009, CV in the lower slope was significantly higher than in the upper slope; in 2010, there was no significant difference among slope positions; in 2011, CV in the lower and middle-lower slopes was significantly higher than in the upper and middle-upper slopes; in 2012, CV in the lower slope was significantly higher than in the upper slope.

The slope variability of CV (29.84%–55.89%) and interannual variability (39.70%–49.06%) were both significantly higher than those of CH (8.26%–12.77%, 9.19%–12.59%).

, , [Figure 2: see original paper]

4.2 Canopy Cover and HLr Dynamics The mean canopy cover (CC) of Daming Mountain evergreen broadleaved forest ranged from 53.55% to 66.92% during 2009-2012, with an average of 59.90%, showing a gradual recovery and increasing trend. Year had an extremely significant effect on CC ($P < 0.001$), with CC in 2011 and 2012 being significantly higher than in 2009 and 2010. Slope position had no significant effect (P = 0.380), and the interaction between slope position and year was not significant (P = 0.103).

The HLr of Daming Mountain evergreen broadleaved forest ranged from 2.10 to 3.14 during 2009-2012, showing a pattern of first decreasing then increasing. Slope position and year had significant effects on HLr ($P < 0.001$, P = 0.013), but their interaction was not significant (P = 0.265). HLr varied among slope positions in different years: in 2009, the middle slope was significantly higher than other positions; in 2010, the middle-lower slope was significantly higher than the middle-upper and upper slopes; in 2011, the lower and middle-lower slopes were significantly higher than the upper slope; in 2012, the lower slope was significantly higher than other positions.

, , [Figure 3: see original paper]

4.3 Canopy LAI Dynamics The mean leaf area index (LAI) of Daming Mountain evergreen broadleaved forest ranged from 1.88 to 2.15 during 2009-2012, with an overall mean of 2.00, showing a weak increasing trend. Slope position and year had some influence on LAI, but both were not significant (P = 0.050, P = 0.083). However, their interaction effect was significant (P = 0.017). LAI at different slope positions varied by year: in 2009, the middle slope was significantly higher than the upper slope; in 2010, the middle slope was significantly higher than other positions; in 2011, the middle-lower slope was significantly higher than other positions; in 2012, there was no significant difference among slope positions.

[Figure 4: see original paper]

4.4 Canopy Vertical Structure and Its Changes Based on statistical results from the three-layer division, the vertical structure of Daming Mountain evergreen broadleaved forest showed upper canopy (>8 m) (canopy cover 42.20%) > middle canopy (4-8 m) (30.35%) > lower canopy (0-4 m) (18.05%). Upper canopy cover was extremely significantly higher than middle and lower canopy ($P < 0.001$), and middle canopy was extremely significantly higher than lower canopy.

The canopy vertical structure of Daming Mountain evergreen broadleaved forest showed some variation among different years and slope positions. The lower canopy cover was smallest in the lower slope, with middle and upper slopes being significantly higher than lower and middle-lower slopes. In 2009, the upper slope was significantly higher than the lower and middle-lower slopes. In 2010, middle canopy cover was also smallest in the lower slope and largest in the upper slope, with upper and middle slopes being significantly higher than lower and middle-lower slopes. In 2011, there was no significant difference in upper canopy cover among slope positions, but both lower and middle canopy covers were highest in the upper slope, with all three canopy layers showing no significant differences among slope positions. In 2012, there was no significant difference in upper canopy cover among slope positions, while middle canopy cover was only significantly higher in the middle slope than in the lower slope, with no significant differences among other positions.

[Figure 5: see original paper]

4.5 Relationship Between Crown Area and DBH There was an extremely significant correlation between crown area and DBH in Daming Mountain evergreen broadleaved forest ($P < 0.001$), with crown area increasing as DBH increased. The increase was greater with longer recovery time, with the largest increase in 2012.

[Figure 6: see original paper]

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5. Discussion

5.1 Basic Characteristics of Canopy Structure in Daming Mountain Evergreen Broadleaved Forest This study shows that the canopy structure characteristics of Daming Mountain evergreen broadleaved forest are: CH (12.09$±0.05)*m*, *CV*(2642.51±278.33)*m*^{3}$ per 400 m^2, CC (59.90$±3.29)±0.23, *andLAI*2.00±$0.06. The canopy structure has multilayer characteristics, with upper canopy cover averaging 42.20%, middle canopy 30.35%, and lower canopy 18.05%. The canopy structure of Daming Mountain evergreen broadleaved forest shows multilayer characteristics, but this differs from the typical subtropical forest characteristic of high multilayer canopy and large LAI [29]. The observed LAI in this study is smaller than that of evergreen broadleaved forest in Ailao Mountain (LAI 5.60) and similar to eucalyptus plantations (2.56), but only averages 2.00.

The lower CH, smaller CV, lower CC, smaller HLr, and LAI in Daming Mountain evergreen broadleaved forest are related to the relatively high elevation (934-1223 m), shallow soil (30-45 cm), and frequent freezing disturbances, especially the severe freezing disaster of 2008. The smaller canopy area may also be related to the CI-110 instrument. Due to frequent freezing disturbances in the montane climate, trees form narrow cylindrical crowns [31], which is the result of long-term adaptation of canopy structure to montane environmental conditions. The formation of this canopy structure characteristic is not only related to the 2008 freezing disaster (in the 3.2 hm^2 fixed plot, the forest gap area formed in 2009 accounted for 71.70% of the expanded gap area, with a tree damage rate of 51.8% for DBH$ $1 cm), but also related to the gradual death of damaged trees after the disaster and climate fluctuations.

5.2 Slope Position Changes in Canopy Structure After Disaster Studies have shown that *Larix principis-rupprechtii* plantations on the southern slope of Liupan Mountain are affected by changing slope environmental conditions, showing slope variation and scale effects. With a slope length increase of 398.2 m horizontally and 188.45 m vertically, LAI shows a fluctuating increasing trend, reaching maximum in the middle slope, demonstrating slope spatial scale effects. That is, for every 100 m slide down the slope, LAI increases by 2.66-3.49. However, slope variation patterns for primary evergreen broadleaved forests over a horizontal slope length of 200 m and vertical length of 160 m have not been reported.

This study shows that canopy structure in evergreen broadleaved forest also shows slope differences, with variation patterns changing by year. In this study, LAI shows a significant slope scale effect, increasing by 0.34 for every 100 m slide down the slope, similar to but weaker than that in *Larix principis-rupprechtii* plantations. This is related to the higher canopy structure and spatial heterogeneity of primary evergreen broadleaved forests. Improving the accuracy of this parameter in ecological models deserves attention in future research, especially for primary evergreen broadleaved forests.

There are few reports on the variation of CV, CC, and HLr with slope position in evergreen broadleaved forests. This study found that these canopy structure indexes also show large variability across slopes (CV: 39.70%-49.06%; CC: 20.35%-24.15%; HLr: 47.33%-57.00%). The authors believe that freezing disturbance is the most direct driving force affecting canopy structure changes, with different slopes experiencing different degrees of damage [33,37], especially short-term fluctuations in the upper canopy, leading to differences in canopy structure across slopes.

5.3 Interannual Dynamics of Canopy Structure After Disaster Disturbance changes the original structure of forest canopy and increases spatial heterogeneity of canopy structure [22,30]. During forest recovery after disturbance, the spatial heterogeneity of canopy structure continues to change and plays a decisive role in forest patterns and ecological processes [30]. Monitoring of evergreen broadleaved forests in northern Guangdong by Yu Duan and Su Zhiyao showed that the overall canopy openness area gradually decreased year by year in the early stage of post-disaster forest recovery, with increasing closure [30].

This study found that after the 2008 freezing disaster, CH, CV, CC, and LAI of Daming Mountain evergreen broadleaved forest showed varying degrees of increase with forest recovery, with the largest increase in 2011. This may be because in the first two years after the disaster, damaged trees gradually died, and the evergreen broadleaved forest recovered slowly. In spring 2010, Daming Mountain evergreen broadleaved forest suffered another strong freezing disturbance, and the recovery rate decreased in 2011. Due to frequent natural disturbances in montane evergreen broadleaved forest regions, the canopy structure is always in a state of constant change.

When studying many key ecological processes, such as canopy interception of precipitation, water evapotranspiration, solar radiation transfer in the canopy, and soil water evaporation under the canopy, ecosystem models should consider not only the spatial heterogeneity of canopy structure but also interannual variations, because the ability to simulate canopy dynamics directly determines the reliability and accuracy of vegetation-atmosphere interface energy exchange in process-based ecosystem models [38-39].

5.4 Relationship Between Crown Area and DBH There is a significant positive correlation between crown area and DBH [40]. Zhang Linan et al. found that the relationship between crown area and DBH in *Larix principis-rupprechtii* plantations is best fitted by a quadratic equation [41], while Hemery et al. found it to be linear [40]. In this study, crown area and DBH show an extremely significant linear relationship ($P < 0.001$), mainly because the DBH of trees in Daming Mountain evergreen broadleaved forest is relatively small. Hemery et al. found that when DBH is 20-50 cm, crown area and DBH show a linear relationship, and most DBH in this study is less than 50 cm. This is consistent with the results of Hemery et al. [40]. The smaller crown area and cylindrical crown shape commonly observed in Daming Mountain evergreen broadleaved forest are the result of long-term adaptation of canopy structure to montane environmental conditions.

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Note: Figure translations are in progress. See original paper for figures.