Front. For. China (2006) 4: 372–378
DOI 10.1007/s11461-006-0041-5

RESEARCH ARTICLE

ZHAO Xiuhai, ZHANG Chunyu, ZHENG Jingming

Correlations between canopy gaps and species diversity in broad-leaved and Korean pine mixed forests

Abstract Regeneration of tree species associated with canopy gaps in broad-leaved Korean pine forests was investigated. Species diversity in gaps and under closed canopy was compared, the relationship between biodiversity and gap structure was analyzed. Results indicate that there were significant differences between tree species diversity in gaps and that under canopy ($p<0.01$). In terms of Shannon-Wiener index, evenness index, and abundance index, the biodiversity in gap community were higher than those under forest canopy in regeneration layer. In terms of Simpson's dominance index, the dominance of certain species in the regeneration layer increased from gaps to closed canopy ($p<0.01$). In contrast, trends of biodiversity changes of succession layer in gaps and under closed canopy were opposite. Tree species diversity of different layers reacted directly to the change of gap size class. For example, Shannon-Wiener index and abundance index is higher and Simpson's dominance index is the lowest in succession layer of medium-size gap (100–250 m^2) in the broad-leaved Korean pine forest of Changbai Mountains. Shannon-Wiener index reached the highest in a size of $\geqslant 250$ m^2 and <100 m^2, reached the lowest in a size of 200–250 m^2 in the regeneration layer. Simpson's dominance index reached its maximum when the gap size was between 200 and 250 m^2. Generally, species of different layers reacted differently to the changes of gap size classes. The gap size class with more seedlings did not correspond to size class containing more medium-size trees. Tree species diversity indices in the two layers behaved reciprocally during the development process of forest gaps.

Translated from *Chinese Journal of Applied Ecology*, 2005, 16(12): 2,236–2,240 [译自: 应用生态学报, 2005, 16(12): 2,236–2,240]

ZHAO Xiuhai (✉), ZHANG Chunyu, ZHENG Jingming
The Key Laboratory for Silviculture and Conservation of Ministry of Education,
Beijing Forestry University,
Beijing 100083, China
E-mail: bfuz@163.com

Keywords forest gap, regeneration, broad-leaved and Korean pine mixed forest, tree diversity, gap structure, stand dynamics

1 Introduction

Forest canopy gaps are the main space where forest regeneration occurs and species coexistence and biodiversity need to be maintained (Thomas and Jerry, 1989; Aguilera and Lauenroth, 1993; Kneeshaw, 1998; Morgan, 1998). There are two major reasons to maintain species diversity of a forest community. The first, called internal reason, is the characteristic difference in species biology and ecology while the other (external region) is the difference of the small-scale bio-environment, that is, the heterogeneity of the ecological environment of tree species (Ye, 2000). Once forest gap has developed, a series of physical and biological environmental changes take place. These changes could enhance the bio-environmental differences. Different tree species require different size of gaps for regeneration. Also, within gaps, regeneration of trees and their ecological characteristics are different (Zhang et al., 1999). Forest gap size or area is a key index to determine the environmental characteristics, the combination of environmental factors and the efficiency of resources within gaps. All these above factors affect the species diversity and regeneration within forest gaps (Platt and Stong, 1989; Liu et al., 2003).

Many previous studies have been conducted on species diversity and stand dynamics (Liu et al., 2003; Sebastiao and Ricardo, 2002; Zang et al., 2002; Bianba et al., 2004). However, only few of them discussed the relationships between gaps and species diversity and special distribution of tree species by using gap layers (Zang et al., 2000; He et al., 2004). Gaps with different sizes and growing stages may have different effects on tree species regeneration. Therefore, the species diversities are different within these gaps (Zang et al., 2000). A forest gap with an appropriate size and age that is best suited for seedlings may not be suitable for future growth and survival of these seedlings (Schupp, 1995). It simply means that their ecological positions are changing during the regeneration of tree species. Therefore, the objectives of this paper are to 1) discuss the species diversity of different growing layers in forest gaps, and the relationship between gap structure and tree species diversity, and 2) provide a theoretical foundation for a better understanding of the correlations among gap size, age, structure, and regeneration of the northeastern Korean pine forests.

2 Site and methods

2.1 Study sites

The study sites are located on the No. 1 standard permanent plots on the northern side of the Forest Ecological System Research Station of Chinese Academy of Science. The site is in the Changbai Conservation region and eastern side of the natural Korean pine protection forest in the Jiaohe Forest Experiment Bureau, Jilin. The climate in the Changbai Conservation region belongs to warm continental mountainous climate, which is dry and windy in spring, warm and rainy in summer, long and cold in winter. The average yearly temperature is 3.3°C. August is the hottest month with an average temperature of 20.5°C and January is the coldest month with an average temperature of –16.5°C. Yearly highest and lowest temperatures are 32.3 and –37.6°C. Average yearly precipitation is 600–900 mm. Soil type is dark brown forest soil with 20 to 100 cm in depth, which is well drained on a slow slope. The eastern slope of the protection area in Jiaohe Experimental Bureau is located at 43°51′–44°05′ N and 127°35′–127°51′ E. This area is hilly with low mountains and continental seasonal climate. Average temperatures are –15°C in January and 23.3°C in July. There are 130 days with temperatures ⩾10°C. Annual precipitation is 800 mm. Soil type is dark brown soil. This area belongs to the Korean pine and spruce mixed forest in Changbai area according to China's biology classification.

Korean pine forest is the regional dominant forest type in the western part of Changbai Mountains. This type of forest is well-known for its special species and diversity. Overstory species include: *Pinus koraiensis*, *Abies holophylla*, *Picea jezoensis*, *Tilia amurensis*, *Juglans mandshurica*, *Ulmus japonica*, *Acer mono*, *Betula costata*, *Fraxinus mandshurica*, *Phellodendron amurense*, *Betula platyphylla*, *Quercus mongolica*, *Acer mandshurica*, *Carpinus cordata* Blume, *Acer ukurunduense*, *Acer pseudosieboldianum*, *Tilia mandshurica* and *Ulmus japonica*. *Pinus koraiensis*, *Picea jezoensis* and *Acer mono* are the dominant species. Understory species include: *Philadelphus schrenkii* Rupr., *Deutzia amurensis* (Regel) Airy-Shaw, *Corylus mandshurica* and *Lonicera japonica* Thunb. Herb species include: *Brachybotrys paridiformis*, *Maianthemum bifolium*, *Phryma leptostachya*, *Carex* spp. and *Impatiens nolitangere*.

2.2 Methods

A total of 89 forest gaps within the study area were investigated, 60 of which were located in Jiaohe and the other 29 were in Changbai Conservation region. Data were recorded for species and regeneration status within gaps and the adjacent areas along the gaps of within 3 m. In gaps, all saplings with height greater than 20 cm were recorded. The length and width of the gaps were also measured, which were later used to calculate the area of a gap as an ellipse. Gaps were classified into four classes based on the status of regeneration 0–20 years, 20–40 years, 40–60 years, >60 years. The canopy gap size was grouped into <100 m^2, 100–150 m^2, 150–200 m^2, 200–250 m^2 and ⩾250 m^2. Diversities for gaps of different age and size were recorded for different layers (regeneration layer: 0.2 m < h <1.5 m, succession layer: h ⩾1.5 m and DBH < 8 cm). The size and structure of the canopy gap are listed in Table 1.

Species diversity index is calculated based on the formula as follows:

Shannon-Wiener diversity index:

$$H = -\sum_{i=1}^{S}(P_i \ln P_i),\ P_i = N_i / N$$

Margalef abundance index: $D = \dfrac{S-1}{\ln N}$

Pielou homogeneity index: $E = \dfrac{H}{\ln S}$

Simpson dominance index: $C = \sum_{i=1}^{S} N_i(N_i - 1) / N(N-1)$

where S is the number of species within the site, N_i is the number of i^{th} species and N is the number of sites.

The dominance index is a quantitative criterion to determine the structure of a biological community by assigning a certain value to each species based on its importance to the whole community. High dominance index simply means that there are only a few dominant species within the group and the group is more stable, and vice versa (Peng, 1987).

Table 1 Size and structure of canopy gap

Research site	Size class of gap area /%					Number of gaps
	< 100 m^2	100–150 m^2	150–200 m^2	200–250 m^2	⩾250 m^2	
Jiaohe	21.7	28.3	23.3	11.7	11.7	60
Changbai Mountains	34.5	20.7	10.3	10.3	24.1	29

3 Analysis and results

3.1 Diversity variation among species

There is a similar diversity changing tendency for Korean pine forest in Changbai Mountains and the Jiaohe area (Fig. 1). Diversity, abundance, and homogeneity indices within forests were significantly higher than those in gaps (p<0.000,1). However, the dominance index is greater than that under canopy in gaps (p<0.000,1). For Changbai Mountain Korean pine forest, both the diversity and abundance indices of the regeneration layer in gaps were higher than those under canopy (p<0.01). The homogeneity index was higher in gaps compared to the index under canopy (p=0.053,3). Reversely, the dominance index under canopy was greater than that in gaps. For the Korean pine forest in Jiaohe, greater diversity, abundance, and homogeneity were more present in gaps than under canopy (p<0.01). However, ecological dominance was higher under canopy.

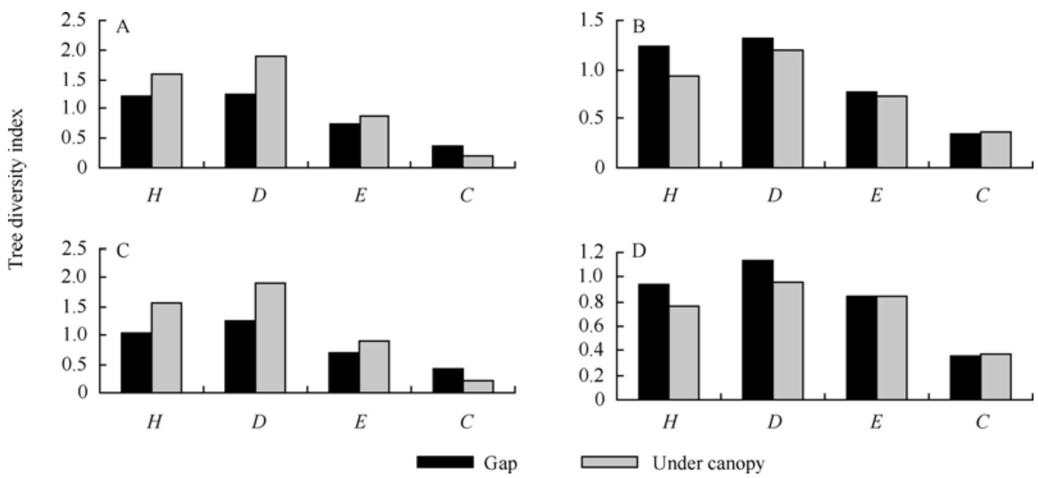
Changes for species diversity varied among different layers within gaps. For the regeneration layer, diversity index, abundance index and homogeneity index increased and the ecological dominance index decreased. For the succession layer, diversity index, abundance index and homogeneity index decreased while dominance index increased. It is slightly different from previous studies, which indicate that the more diverse the tree species in gaps the less dominant these trees are (Zang and Xu, 1999; Zang et al., 1999, 2000; Liu and Wu, 2002; Luo et al., 2002; He et al., 2004). Compared to the control site, the species of the succession layer in gaps have higher dominance indices and the dominant species have significant impacts on other species. However, in the regeneration layer, there were no obvious dominant species and dominance indexes were lower. This means the group becomes more diverse and homogeneous with several coexisting competitive species (Miguel et al., 1989), which is consistent with regeneration and dynamics of species in gaps (Hutinik, 1952; Schupp et al., 1989; Zang et al., 1999, 2002).

3.2 Gap size and species diversity

3.2.1 Changbai Mountains

For the succession layer, the diversity and abundance indices varied in a single peak curve. Higher diversity index and homogeneity index occurred in gaps of medium size (100–250 m^2), which reached their minimums when the gap size was between 100 and 250 m^2. Ecological dominance index reached its maximum when the gap size was between 100 m^2 and 250 m^2, or ⩾250 m^2 or ⩽100 m^2. For the succession layer, homogeneity index had the maximum value when the gap size was ⩽100 m^2, and had minimum value when the gap size was ⩾250 m^2. When the gap size was between 100–250 m^2, the homogeneity index varied slightly (Table 2).

For the regeneration layer, diversity index and homogeneity index reached their maximums when the gap size was ⩾250 m^2 or <100 m^2 while they have the minimum values when the gap size was between 200 and 250 m^2. Dominance index changed in the opposite way as a single peak curve, which had the maximum value when the gap size was between 200 and 250 m^2 and had minimum value when the gap size was less than 100 m^2 or ⩾250 m^2. Species diversity index also increased as the gap size increased (Table 2).



A. Succession layer of Changbai Mountain; B. Regeneration layer of Changbai Mountain;
C. Succession layer of Jiaohe; D. Regeneration layer of Jiaohe

Fig. 1 The contrast of tree diversity in gaps and under canopy

Table 2 Tree diversity in gaps in different size class

Layer	Gap size	Tree diversity index of Changbai Mountain				Tree diversity index of Jiaohe			
		H	D	*E*	*C*	*H*	*D*	*E*	*C*
A	S_G<100	0.911,6	0.503,7	0.829,8	0.434,0	0.926,5	1.172,5	0.671,2	0.455,7
	100≤S_G<150	1.275,5	1.331,2	0.702,6	0.344,9	0.994,1	1.210,2	0.687,4	0.434,1
	150≤S_G<200	1.168,4	1.291,2	0.715,7	0.394,8	1.049,4	1.241,6	0.698,2	0.418,6
	200≤S_G<250	1.398,8	1.463,0	0.769,6	0.310,2	1.060,0	1.238,8	0.700,4	0.422,8
	250≤S_G	1.076,1	1.207,7	0.526,7	0.498,8	1.182,4	1.377,3	0.767,0	0.368,1
B	S_G<100	1.290,7	1.176,1	0.802,0	0.305,8	0.808,9	0.945,7	0.761,7	0.450,7
	100≤S_G<150	1.167,6	1.223,9	0.779,0	0.362,6	0.984,5	1.210,2	0.870,9	0.288,2
	150≤S_G<200	1.268,0	1.372,3	0.761,7	0.344,5	0.985,3	1.290,1	0.809,5	0.350,9
	200≤S_G<250	1.032,0	1.410,8	0.640,9	0.438,5	0.945,7	1.204,7	0.961,6	0.214,8
	250≤S_G	1.688,3	1.438,6	0.867,6	0.196,2	0.948,9	1.050,9	0.869,0	0.367,6

A: Succession layer; B: regeneration layer.

3.2.2 Korean pine forest in Jiaohe

For the succession layer, diversity index, abundance index and homogeneity index had similar changing trends. They reached their maximum values when the gap size was ⩾ 250 m^2, minimum values when the gap size was less than 100 m^2, and slight changes when the gap size was between 100 and 250 m^2. Dominance index has the opposite changing trend. It had its minimum value when the gap size was ⩾250 m^2, maximum value when the gap size was less than 100 m^2, and slight changes when the gap size was between 100 and 250 m^2. This means that, for Jiaohe Korean pine forest, diversity index, abundance index and homogeneity index increased and the dominance index decreased as the gap size increased.

Higher diversity, abundance, and homogeneity indices occurred in gaps of medium size (100–200 m^2). Relatively lower diversity, abundance, and homogeneity indices existed present when the gap size was ⩾250 m^2 or less than 100 m^2. However, the ecological dominance index reached its maximum value when the gap size was ⩾250 m^2 or less than 100 m^2. Dominance index had relatively lower value when the gap size was between 100 and 250 m^2 (Table 2).

Species diversity of different layers had different reactions to gap size. This might be explained by different terrain, altitude and micro-climate in a specific area (Runkle, 1990). Gap size is critical to the status of certain ecological factors, especially light intensity, which has an important effect on tree species within gaps and their distribution (Thomas and Jerry, 1989). Based on the light intensity to analyze the correlation between gap size and diversity, 20 representative forest gaps were selected in Jiaohe. The light intensity was measured at 1.5 m above the ground at noon time. The species diversity index and area for each layer within forest gaps were computed. Results indicated that the light intensity generally increased with an increment of the gap size (Fig. 2). Diversity in the regeneration layer was positively related to the light intensity. There was no significant relationship between the diversity index of the succession layer and the light intensity, which demonstrated a single peak curve (maximum value appeared at 3,500–5,000 lx) (Fig. 3). Therefore, the diversity index of the regeneration layer was positively related to the gap size, which meant the diversity index increased as the gap size increased. In the succession layer, the correlation between the diversity index and the gap size presented a single peak curve, which reached its maximum value in gaps of medium size. These findings are consistent with previous studies. Therefore, further studies on ecological factors and their combined characteristics are essential in order to achieve a better understanding of the correlation between forest gap size and species diversity under different layers in different regions.

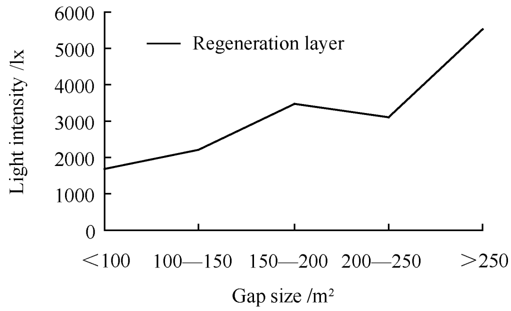


Fig. 2 The change of light intensity with gap size

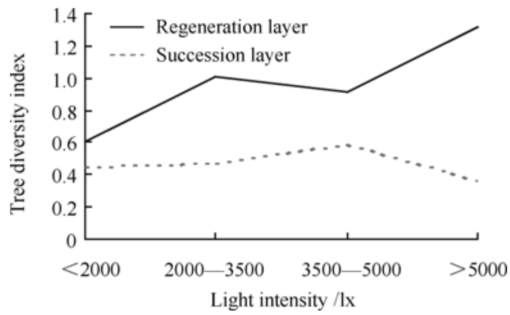


Fig. 3 The change of tree diversity with light intensity

3.3 Forest gap development and species diversity

3.3.1 Changbai Mountain Korean pine forest

Higher diversity and homogeneity indices existed in 0–20 years and 40–60 years age classes in the succession layer while the lowest values of these two indices were in the age class of 20–40 years. As the age class increased, homogeneity index decreased and the ecological dominance index increased. In the regeneration layer, higher diversity, abundance, and homogeneity indices occurred in the 0–20 years age class while their minimum values were present in the 20–40 years age class. The ecological dominance index reached the maximum value in the 20–40 years age class and minimum value in 0–20 years age class (Fig. 3).

3.3.2 Jiaohe Korean pine forest

Species diversity, abundance, and homogeneity indices in the succession layer reached their maximum values in the 20–40 years age class and minimum values in the 0–20 years and 40–60 years age classes. The ecological dominance index reached its maximum value in the 0–20 years age class and the minimum value in the 20–40 years age class. In the regeneration layer, species diversity, abundance, and homogeneity indices presented higher values in the 0–20 years and 40–60 years age classes, and minimum values in the 20–40 years age class. Dominance index reaches its maximum value in the 20–40 years age class and minimum value in the 0–20 years and 40–60 years age class.

4 Conclusions and discussion

1. Species in different layers within forest gaps have different reactions to the gap size. A better gap size or area for seedling development in the regeneration layer may not necessarily be the best suitable gap area for sapling survival in the succession layer (Schupp, 1995; Liu and Wu, 2002; Luo et al., 2002). This means that gap size is an important factor that will affect the future species composition in gaps. Generally speaking, a larger gap is good for the regeneration of shade-intolerant species and a smaller gap can enhance the regeneration of shade-tolerance species. A forest gap of certain size can benefit all species within it. What is the gap size best suited for regeneration? Because of the different climate and forest type, the answers are different for different areas. He et al. (2004) reported that the gap size of less than 100 m^2 is better for species diversity and protection. Luo et al. (2002) indicated that the gap size of about 100 m^2 is better for regeneration of seedlings of less than or equal to 20 cm in height. He also found out that the gap size of 300 m^2 is best suited for the growth of saplings and trees with small diameters. For south-Asian evergreen broad-leaved tropical forest, Zang et al. (2000) reported that when gap size is between 400 and 500 m^2, there is the greatest potential for species diversity within gaps. It is meaningful to determine the "best" gap size by monitoring a study site for a long time period, which is also something we are planning to accomplish in the future.

2. Forest gap is a critical space for tree regeneration (Aguilera and Lauenroth, 1993; Morgan, 1998; Zhu and Li, 2002). With the change of microenvironment (light, temperature, moisture, soil, and others), the usable resources will be enhanced within gaps. As shade-intolerant species invade and coexist with shade-tolerant species, species diversity and abundance will be improved at an earlier stage of regeneration. The dynamic change of species diversity within forest gaps is the result of the interaction among tree physiological and ecological characteristics and the microenvironment in forest gaps. It reflects the dynamic requirements of natural recourses like sunshine, temperature and water during different development phases of species. During the process of seedling growth, some species can be eliminated due to their own characteristics and the microenvironment in gaps. Only some of the tree species can grow into a succession layer (Luo et al., 2002). In comparison with trees adjacent to the gap, there are more trees eliminated in gaps. Therefore, the succession layer within gaps has relatively lower diversity and species abundance.

Table 3 Tree diversity in gaps in different age class

Layer	Gap age class	Tree diversity index of Mt. Changbai				Tree diversity index of Jiaohe			
		H	*D*	*E*	*C*	*H*	*D*	*E*	*C*
A	0–20 years	1.729,5	1.374,5	0.965,3	0.165,0	0.859,9	0.905,9	0.659,6	0.501,9
	20–40 years	1.154,4	1.188,4	0.823,5	0.316,1	1.248,3	1.474,7	0.838,0	0.279,0
	40–60 years	1.301,5	1.455,7	0.683,8	0.372,2	0.787,3	1.037,5	0.638,7	0.482,6
	>60 years	1.183,2	1.234,6	0.676,0	0.400,5	1.195,3	1.416,6	0.733,3	0.370,7
B	0–20 years	1.418,1	1.559,5	0.881,1	0.230,8	1.149,1	1.365,4	0.828,9	0.305,6
	20–40 years	1.025,7	1.208,0	0.706,8	0.428,9	0.653,7	0.740,8	0.576,0	0.646,5
	40–60 years	1.225,6	1.426,2	0.718,4	0.366,2	1.027,9	1.420,8	0.950,3	0.211,0
	>60 years	1.230,6	1.272,4	0.769,6	0.348,2	0.931,7	1.094,8	0.844,0	0.350,2

3. The species diversity Shannon-Wiener index of the regeneration layer for northern temperate broad-leaved Korean pine forest is lower than that of central Asian tropical evergreen broad-leaved forest (Shannon-Wiener index 2.444,2–3.078,1) and southern Asian tropical evergreen broad-leaved forest (Shannon-Wiener index 1.652–2.286) (Zang et al., 2002; He et al., 2004). For succession layer, the Shannon-Wiener index is also lower than that of central Asian tropical evergreen broad-leaved forest (Shannon-Wiener index =1.815,4–2.900,5). It is probably because the continental mountain climate in the northern temperate region is influenced by seasonal wind. The yearly average temperature is only 3.3°C and the yearly average rainfall is between 600 and 900 mm. However, for sub-tropical region, the annual average temperature is 17.7–19.6°C and yearly average rainfall is 1,743.8–1,782.5 mm. Due to these reasons, the diversity indexes for all layers in gaps are higher than those for Korean pine forests in the northern temperature region.

4. Many researchers have proved that the species diversity within gaps can be enhanced by changing the ecological factors like light and temperature. For example, in the Wuyi Mountains, Fujian province, the diversity index, abundance index and evenness index within gaps are higher than those under forest canopy (He et al., 2004). In Jinyun, Chongqing, the forest gaps presented a significant higher species diversity index in comparison to under canopy (Qi et al., 2001; Wang et al., 2003). In the Maolan Karst, Guizhou province, the diversity index, abundance index and homogeneity index are also significantly greater than those under canopy (Long et al., 2005). However, further study still needs to be conducted on the correlation between the number of species within each layer and microenvironment within gaps, and type of ecological factors that determine the diversity variation within gaps.

Acknowledgements This project was funded by National 11st Five-year Project of China: Protection and Sustaining Management Techniques of Natural Forests in Northeast China.

References

Aguilera M. O., Lauenroth W. K., Seedling establishment in adult neighborhoods-intraspecific constrains in the regeneration of the bunchgrass *Bouteloua gracilis*, J. Ecol., 1993, 81: 253–261

Bianba D. J., Guo Q. S., Ci B., Luo D. Q., Effects of gap in primitive subalpine fir forest on diversity of herb and shrub in Tibet, Chin. J. Appl. Ecol., 2004, 15(2): 191–194 [边巴多吉, 郭泉水, 次柏, 罗大庆, 西藏冷杉原始林林隙对草本植物和灌木树种多样性的影响, 应用生态学报, 2004, 15(2): 191–194]

Geng Y. Q., Shan H. C., Tan X., Sun X. Y., Wang D. Z., Studies on soil in forest gap in artificial needle forest, J. Beijing For. Univ., 2002, 24(4): 16–19 [耿玉清, 单宏臣, 谭笑, 孙向阳, 王登芝, 人工针叶林林冠空隙土壤的研究, 北京林业大学学报, 2002, 24(4): 16–19]

He G. S., Lin S. Z., Cao Z. L., Zhao D. Z., Lai D., A comparing study on the tree species diversities of gaps in natural evergreen broad-leaved forest in Mountain Wuyi, Chin. J. Ecol-Agric., 2004, 12(1): 70–73 [何国生, 林思祖, 曹子林, 赵大洲, 来端, 武夷山天然常绿阔叶林林隙物种多样性比较研究, 中国生态农业学报, 2004, 12(1): 70–73]

Hutinik R. J., Reproduction in wind-falls in a northern hardwood stand, J. For., 1952, 50: 693–694

Kneeshaw D. D., Canopy gap characteristic and tree replacement in the southeastern boreal forest, J. Ecol., 1998, 79: 783–794

Liu J. F., Hong W., Li J. Q., Lin R. F., Gap edge effect of *Castanopsis kawakamii* community, Chin. J. Appl. Ecol., 2003, 14(9): 1,421–1,426 [刘金福, 洪伟, 李俊清, 林荣福, 格氏栲群落林窗边缘效应研究, 应用生态学报 2003, 14(9): 1,421–1,426]

Liu Q., Wu Y., Effects of gap size on regeneration of subalpine coniferous forests in northwest Yunnan, Chin. J. Appl. Environ. Biol., 2002, 8(5): 453–459 [刘庆, 吴彦, 滇西北亚高山针叶林林窗大小与更新的初步分析, 应用与环境生物学报, 2002, 8(5): 453–459]

Long C. L., Yu S. X., Xiong Z. B., Wei L. M., Species diversity and regeneration in forest gaps of the Karst forest in Maolan National Nature Reserve, Guizhou Province, Biodivers. Sci., 2005, 13(1): 43–50 [龙翠玲, 余世孝, 熊志斌, 魏鲁明, 茂兰喀斯特森林林隙的植物多样性与更新, 生物多样性, 2005, 13(1): 43–50]

Luo D. Q., Guo Q. S., Xue H. Y., Bianba D. J., Pan G., A research of gap regeneration of virgin fie forest in Mount Ssjila in Tibet, For. Res., 2002, 15(5): 564–569 [罗大庆, 郭泉水, 薛会英, 边巴多吉, 潘刚, 西藏色季拉山冷杉原始林林隙更新研究, 林业科学研究, 2002, 15(5): 564–569]

Miguel M. R., Elena A. B., Jose S., Tree demography and gap dynamics in a tropical rain forest, Ecology, 1989, 70(3): 555–558

Morgan J. W., Importance of canopy gaps of recruitment of some forbs in *Themeda triandra*-dominated grasslands in south-eastern Australia, Austral. J. Bot., 1998, 46: 609–629

Peng S. L., Ecological dominance of forestry community in subtropics of Guangdong, Acta Ecol. Sin., 1987, 7(1): 36–42 [彭少麟, 广东亚热带森林群落的生态优势度, 生态学报, 1987, 7(1): 36–42]

Platt W. J., Stong D. R., Special feature-gaps in canopy ecology, 1989, Ecology, 70: 11

Qi D. H., Li X. G., Wang Z. P., Shi S. Y., He Z. M., Xu W. W., Deng X. B., Preliminary research on species diversity change of the regeneration layer in gap gradient in the coniferours-broadleaved forest in Jinyun Mountain, Biodivers. Sci., 2001, 9(1): 51–55 [齐代华, 李旭光, 王周平, 石胜友, 何正明, 许文蔚, 邓先宝, 缙云山针阔混交林更新层物种多样性林隙梯度变化初探, 生物多样性, 2001, 9(1): 51–55]

Runkle J. R., Gap dynamics in an Ohio *Acer-Fagus* forest and speculations on the geography of disturbance, Can. J. For. Res., 1990, 20: 632–641

Schupp E. W., Howe H. F., Augspurger C. K., Levey D. J., Arrival and survival in tropical treefall gaps, Ecology, 1989, 70(3): 562–564

Schupp E. W., Seed-seedling conflicts, habitat choice and patterns of plant recruitment, Am. J. Bot., 1995, 82: 399–409

Sebastiao V. M., Ricardo R. R., Gap-phase regeneration in a semideciduous mesophytic forest south-eastern Brazil, Plant Ecol., 2002, 165: 1–12

Sha L. Q., Cao M., Studies on soil fertility in forest gap and understory in tropical seasonal rain forest in Xishuanbannna, J. Northeast For. Univ., 1999, 27(6): 78–80 [沙丽清, 曹敏, 西双版纳热带季节雨林林冠下及林窗中土壤养分对比研究, 东北林业大学学报, 1999, 27(6): 78–80]

Thomas A. S., Jerry F. F., Gap characteristics and vegetation response in coniferous forests of the patch northwest, Ecology, 1989, 70(3): 543–545

Wang Z. P., Li X. G., Shi S.Y., Qi D. H., A comparison study on the species diversity between the gap and non-gap in Jinyun Mountain, Chin. J. Appl. Ecol., 2003, 14(1): 7–10 [王周平, 李旭光, 石胜友, 齐代华, 何正明, 许文蔚, 邓先宝, 缙云山森林林隙与非林隙物

种多样性比较研究, 应用生态学报, 2003, 14(1): 7–10]
Ye W. H., The maintenance mechanism of plant community and its species diversity, Chin. Biodivers., 2000, 8: 17–24 [叶万辉, 物种多样性与植物群落的维持机制, 生物多样性, 2000, 8: 17–24]
Zang R. G., Jiang Y. X., Yu S. X., The forest cycle and tree species diversity dynamics in a tropical mountain rain forest of Hainan Island, South China, Acta Ecol. Sin., 2002, 22(1): 24–32 [臧润国, 蒋有绪, 余世孝, 海南霸王岭热带山地雨林森林循环与树种多样性动态, 生态学报, 2002, 22(1): 24–32]
Zang R. G., Liu J. F., Dong D. F., Gap Dynamics and Forest Diversity, Beijing: China Forestry Publishing House, 1999: 4－112 [臧润国, 刘静芳, 董大方, 林隙机制与森林生物多样性，北京：中国林业出版社, 1999: 4–112]
Zang R. G., Wang B. X., Liu J. Y., Tree species diversity in gaps of different sizes and development stages in lower subtropical evergreen broadleaved forest, South China, Chin. J. Appl. Ecol., 2000, 11(4): 485–488 [臧润国, 王伯荪, 刘静艳, 南亚热带常绿阔叶林不同大小和发育阶段林隙的树种多样性研究, 应用生态学报, 2000, 11(4): 485–488]
Zang R. G, Xu H. C., Canopy disturbance regimes and gap regeneration in a Korean pine-broadleaved forest in Jiaohe, Northest China, Bull. Bot. Res., 1999, 19(2): 232–240 [臧润国, 徐化成, 蛟河阔叶红松林林冠干扰及林隙更新研究, 木本植物研究, 1999, 19(2): 232–240]
Zhang Y. P., Liu Y. H., Ma Y. X., Wang J. X., The Spatial characteristics of air temperature in canopy gap in a tropic secondary forest in Xishuangbanna, Acta Ecol. Sin., 2001, 21(2): 211–215 [张一平, 刘玉洪, 马友鑫, 王进欣, 西双版纳干季晴天次生林林窗气温时空分布特征, 生态学报, 2001, 21(2): 211–215]
Zhang Y. P., Wang J. X., Liu Y. H., Ma Y. X., Analysis on characteristics of the spatial variation of average air temperature in tropical secondary forest canopy, Chin. J. Ecol., 2001, 20(2): 1–4 [张一平, 王进欣, 刘玉洪, 马友鑫, 热带次生林林窗平均气温空间分布特征的初步分析, 生态学杂志, 2001, 20(2): 1–4]
Zhu X. L., Li Z. J., A preliminary study on tree species regeneration in sub tropics rain forest in Nanjing and Xinan, J. Xiamen Univ. (Nat. Sci.), 2002, 41(5): 589–595 [朱小龙, 李振基, 南靖和溪南亚热带雨林林隙内树种更新初步研究, 厦门大学学报(自然科学版), 2002, 41(5): 589–595]