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Dynamics of leaf area index and canopy openness of three forest types in a warm temperate zone

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Abstract Deciduous broad-leaved forests (DBF), *Larix principis-rupprechtii* (LF) and *Pinus tabulaeformis* plantations (PF) are three typical forest communities in the warm temperate zone of the Dongling Mountains. In this study, we used an indirect method, hemispheric photography, to measure and analyze the dynamics of leaf area index (*LAI*) and canopy openness of the three forest communities. The results show that the *LAI* values of DBF and LF increased gradually with plant growth and development. The highest *LAI* value appeared in August, while canopy openness changed inversely with *LAI*. The lowest value appeared in November. DBF maintained a higher *LAI* in August and had a more open canopy in November compared with LF. For PF, we observed little changes in the *LAI* and canopy openness which was attributed to the leaf retention of this evergreen species. However, a similar relation between *LAI* and canopy openness was found for the three forest communities: canopy openness varied inversely with *LAI*. The relation is exponential and significant. Therefore, canopy openness is a good indicator of *LAI* in forests. This result can be used to test the validity of the *LAI* based on remote sensing and to provide a reference for the study of the canopy heterogeneity and its effect. This also benefits modeling for fluxes of carbon, water and energy from the level of the stand to landscape.

Keywords leaf area index (*LAI*), canopy openness, dynamics

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1 Introduction

Leaf area index (*LAI*) and canopy openness are both important indices of forest canopy structures. A canopy structure does not only affect the capture of solar radiation, but also affects the entire photosynthetic process of the forest through the interaction of plants and the environment, which is conducted by the exchange of water, heat, gas and other micro-environment factors in the forest (Fang, 1998).

Leaf area index, as a measure of forest canopy structure, was proposed by the British agricultural ecologist Watson in the middle of 1940s and is directly related to many biological and physiological processes, such as interception, respiration, transpiration, etc. Therefore, *LAI* has a direct impact on the efficiency of solar energy utilization and has become an important indicator in describing canopy structure of trees and the photosynthetic rate of different plant layers. The productivity of the community is decided by these two factors (Zhang, 1990). *LAI* represents one side of a leaf, that is half areas of all leaf areas, and it has no unit (Wang, 2005). Several research results show that *LAI* is an important index in modeling evapotranspiration at the canopy level (Mcnaughton and Jarvis, 1983), as well as at the landscape level (Running and Coughlan, 1988; Zhu et al., 2001). Forest *LAI* is one of the essential parameters in the process model of an ecosystem development, which plays an important role in estimating the flux of carbon, water and energy at the forest level and other large areas.

Canopy openness is the open area at the canopy level uncovered by the branches and leaves, measured at one point when viewed upwards to the canopy level in the forest. Canopy openness = 1 – canopy closure (the proportion of woodland area covered by the vertical projection of the canopy, similar to vegetation coverage in ecology (Zhu, 2003). This index is usually used in studies of ecosystem productivity (Vales and Bunnell, 1998; Zhu, 2003). Canopy openness can only be measured by a hemispheric photograph and it is not affected by the surrounding terrain (Frazer et al., 1999).

A number of studies have been carried out in the warm temperate forests of China, but only a few about the leaf area index of deciduous forest communities and their canopy openness. The dynamics of leaf area index and canopy openness have close relations with forest ecosystem research. 1) The dynamics of *LAI* can relate plant growth to remote sensing characteristics. With the development in measurements and application technologies of remote sensing, it is an effective way to obtain the *LAI* of large regions with the help of optical remote sensing technologies. However, the *LAI* estimated by remote sensing methods must be verified on the ground (Gholz, 1982; Pierce and Running, 1988; Li and Wang, 1995; Hu and Shao, 2001; Zhang, 2001; Zhao et al, 2002; Fang and Zhang, 2003; Hui et al, 2003). It is necessary therefore to obtain accurate *LAI* measurements on the ground, either directly or indirectly. 2) Research into the distribution and dynamics of *LAI* is the key to estimate forest productivity (Lassoies and Hinckely, 1991; Zhu et al., 2001). Fast and accurate *LAI* estimates can help obtaining the information about forest carbon, energy and water fluxes at local, landscape and regional levels. 3) Referring to the relationship between productivity and water, rules of the dynamics of *LAI* in temperate forests can provide important theoretical and practical guidelines in the restoration of vegetation, tree species selection and forest management. 4) The dynamics of canopy openness is a surrogate of dynamic canopy structures and growth and it can provide important information about the heterogeneity of the tree canopy in the research area and the impact from heterogeneity, which covers the spatial variation of forest soil moisture, soil organic matter and so on. We obtained the *LAI* and canopy openness of three different temperate forest types with hemispheric photography and conducted an integrated comparison of the two indices among the three types of forest. A relationship between the two indices was found after analyzing their seasonal dynamics. Some other characteristics of the *LAI* and canopy openness in different types of temperate forest have also been obtained, providing a basis for further study.

2 Study site

The study was carried out at the Beijing Forest Ecosystems Research Station of the Chinese Academy of Sciences, located in the Dongling Mountains of Beijing. The station is between latitudes 39°48'–40°00'N and longitudes 115°24'–115°36'E. This area has a temperate continental monsoon climate with an average annual precipitation of 500–650 mm. The average annual temperature is 5°C–11°C. The hottest month is July with an average monthly temperature of 18°C–25°C, while the coldest month is January, with an average monthly temperature of –4°C–10°C. The soil types of this region are

cinnamon soil, brown soil, subalpine meadow soil and so on.

The main vegetation types of this region are cold temperate coniferous plantations, temperate coniferous plantations, deciduous broad-leaved forests, deciduous broad-leaved shrubs and meadows (Chen and Huang, 1997). Temperate zone deciduous broad-leaved forest is the dominant vegetation type in this area, which reflects its atmospheric water and moisture conditions. The forests in the Dongling Mountains are a significant representation of several types of temperate forest ecosystems in China.

The deciduous broad-leaved forest (DBF, plot size 30 m × 75 m), in which *Quercus liaotungensis* is the dominant species, the *Larix principis-rupprechtii* forest (LF, plot size 30 m × 40 m) and the *Pinus tabulaeformis* forest (PF, plot size 30 m × 30 m) form our three research forest communities and they are, in turn, the representative community types of temperate deciduous broad-leaved forests, deciduous coniferous forests and evergreen coniferous forests (Chen and Huang, 1997).

Table 1 General information of three forest communities

item	DBF	LF	PF
elevation/m	1200	1200	1150
slope	28°	26°	30°
aspect	N35°W	N40°W	N60°E
density/trees·hm ⁻²	1262	2700	2000
diameter at breast height (DBH)/cm	12.2	14.8	17.5
height/m	6.8	17	18

3 Methods

The sampling scheme in the DBF (30 m × 75 m) is shown in Fig. 1 and the samplings in LF and PF were conducted in the same way. The distance between two sampling points is 10 m and we constructed a 4 × 8 observation grid. A digital camera, NIKON995, equipped with the fisheye lens, NIKON FC-E8, was fixed on a tripod, 1.5 m above the ground. On observation, the camera was set as a fisheye mode to make a hemispheric photograph at every point in the process. The measurements were conducted along the grid. In order to avoid movement of the camera, the photographs were shot by the camera in auto mode. Photographs were made four times at the same point in four representative times of the year, i.e. May (leaf growth period), August (period of lush leaves), September (before leaf fall), and November (after leaf fall). The best times for making photographs are on cloudy days, when sunlight can be transmitted uniformly. Other good times are just before sunrise or after sunset on sunny days, because the scattered radiation of the sun is low at this time. The worst times are sunny days and in the middle of the day, when the clouds are distributed unevenly and when *LAI* will be underestimated and scattered solar radiation will be overestimated in

the former case and the incident sunlight changes quickly in the middle of the day (Zhao, 2002). Our observations were all conducted at suitable times. We also chose days with light or no wind, in order to make sure that the leaf images were clear.

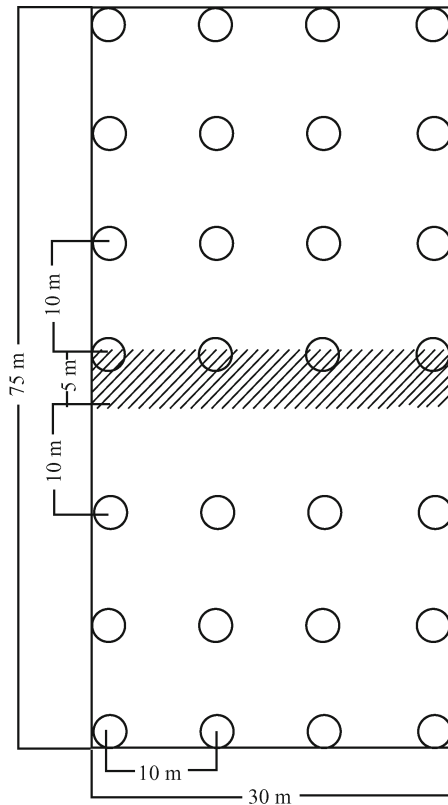


Fig. 1 Sampling scheme for hemispheric photography
○: locations for measurement

4 Results

4.1 Seasonal dynamics of LAI in three forest communities

The seasonal dynamics of LAI in three different forests are shown in Fig. 2. The values of LAI in both DBF and LF show an increasing trend with the arrival of the growing season and have a single peak appearing in August. The values are averages of the four measurements taken at each plot during the same month. The peak LAI of DBF is 2.90 ± 0.09 (mean \pm sd) and that of LF is 2.54 ± 0.08 . In September, the values of LAI show a significant decrease until the end of the season. The LAI in DBF clearly varied more than that of the other two forest types and increased 22% from May to August and then decreased by 82% in November. The variation of LAI in LF is not as large as that in DBF, its increase is only 1.6% and declined by 63%. The LAI in PF varied only a little around a value of 2.00. Its maximum appeared at May, with a peak value

of 2.30, while its minimum was 1.91 in November. There was a weak decline of only 17% in the LAI of PF from May to November. The order of mean LAI values in three forests is PF > DBF > LF, with mean values of 2.14, 2.00 and 1.98, respectively.

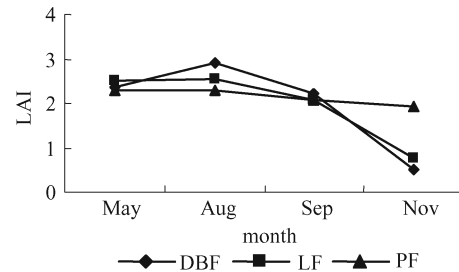


Fig. 2 Dynamics of LAI for the three forest communities

4.2 Seasonal dynamics of canopy openness in three forest communities

Seasonal dynamics of canopy openness in the three forest communities are shown in Fig. 3. As the opposite of LAI, canopy openness shows a tendency to decrease with the arrival of the growing season in DBF and LF, with minima of 8.58% (DBF) and 10.87% (PF) in August. From September, the index began to increase. The variation of canopy openness in DBF is large and varied from 8.6% in August to 45.8% in November. Canopy openness in PF increased from 10.9% in August to 37.8% in November. From May to November the values of canopy openness in PF were 12.7%, 12.8%, 14.9% and 16.8% respectively, with an average value of 14.3%, which is close to the canopy openness value of DBF and LF in August and September. The order of the mean canopy openness in the three forests is DBF > LF > PF, and the mean values are 20.88%, 20.19% and 14.31%, respectively.

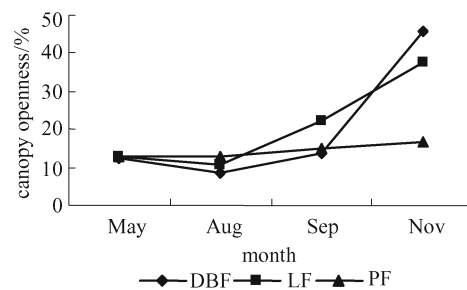


Fig. 3 Dynamics of canopy openness for the three forest communities

4.3 Relationship between LAI and canopy openness in three forest communities

There was a negative exponential relationship between LAI and canopy openness in the three forest communities

(Fig. 4), and canopy openness decreases with the growth of *LAI*, or with the closing of the canopy. Statistically, the relation is highly significant.

4.4 Canopy uniformity of three forest communities

The canopy uniformity of the three forest communities is analyzed based on the data in August, with the peak *LAI* values occurring. *CV* (coefficient of variation) of *LAI* in PF is the minimum, which indicates larger canopy uniformity in PF than that in the other two communities. The rank of canopy uniformity of three forest communities is PF > LF > DBF (Table 2).

5 Discussion

5.1 Prospect of research about *LAI* in warm temperate zone

The *LAI* in a warm temperate zone was accurately measured by hemispheric photography in our study. In future research, the relationships between *LAI* and precipitation, temperature and other weather factors should be considered with the help of remote sensing data and biological and climatic data in the area. This research revealed some sensitive variation and annual large-scale vegetation dynamics as a response to seasonal changes and found some internal reasons and physical mechanisms for the different characteristics from the aspect of geophysics, ecology, climatology and so on (Li et al., 1995; Wang et al., 2005).

LAI is an important intermediate variable in some forest growth models, such as BIOME-BGC. The accuracy of *LAI* has a direct impact on the estimation results of other parameters. The estimation about actual *LAI* dynamics has not been solved. In this research, the variation in the *LAI* of deciduous communities is significant and the change in annual climate, such as wind, can also contribute to the variation in *LAI*. However, we usually use one single unchanged *LAI* as model parameter to describe the canopy characteristics. The accuracy of the

LAI parameter in the ecology model, especially the variation of *LAI* over time and space, deserves more attention in future research.

5.2 Efficient *LAI* and *LAI*

These days, the measurement methods for *LAI* have been divided as direct and indirect. The direct methods include a litter collection method, destructive sampling and allometric growth equations. Most of the direct methods are based on traditional stem analysis. However, the disadvantages are the destruction of trees and sampling errors (Zhang et al., 2004). Indirect methods measure the radiation transmittance with the help of optical instruments such as *LAI*-2000 Plant Canopy Analyzer (LI-COR Inc., USA), Tracing Radiation and Architecture of Canopies (TRAC), Digital Hemispheric Photography (DHP) and the Demon Sunfleck Ceptometer. The *LAI* then was calculated from the radiation data. TRAC is the only one instrument that can measure collection index (Ω) (Zhou et al., 2003). Many studies have shown that *LAI* estimated from optical data is lower than that obtained by direct methods (Fassnacht et al., 1994).

Jonckheere et al. (2004) pointed out that the hemispheric photo method not only measures *LAI*, but also obtains more information about the canopy structure than other optical equipments, which is the reason why we chose this method to conduct our research. The *LAI* measured is efficient *LAI*, i.e., the impacts caused by the aggregated effect of leaves, while other parts of the tree, such as the stems and branches which are not leaves, are not considered. The removal of the aggregated effect of leaves can add to the value of *LAI*, while the removal of the non-leaf parts can decrease its value. In temperate deciduous broad-leaved forests, the two removals counteract each other, so *LAI* does not change much after these two eliminations. The real *LAI* can be estimated from the efficient index in temperate deciduous broad-leaved forest (Eriksson et al., 2005). Removals are mainly applied in coniferous forests (Chen, 1996; Chen and Cihlar, 1996; Kucharik et al., 1998), because the impacts caused by the aggregated effect of

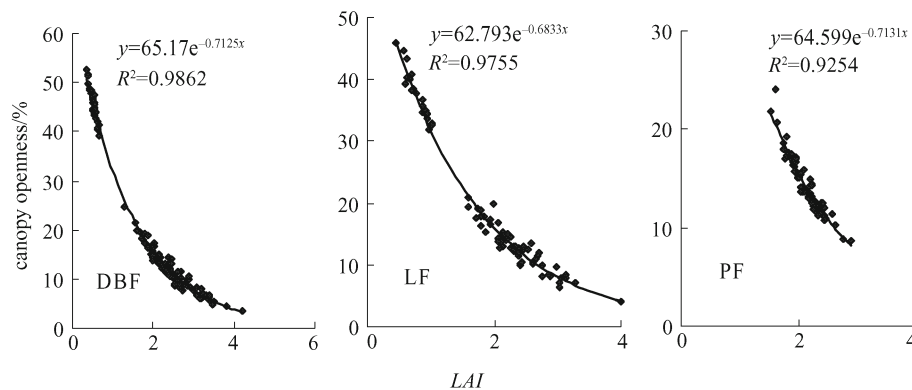


Fig. 4 Negative exponential relationships between *LAI* (x) and canopy openness (y) in three forest communities

Table 2 *LAI* and *CV* (coefficient of variation) for the three forest communities in August

community type	<i>LAI</i>	<i>CV</i> /%
DBF	2.90 ^a ± 0.52	17.93
LF	2.54 ^b ± 0.36	14.17
PF	2.28 ^c ± 0.24	10.53

Note: Different letters means significant difference at $p < 0.01$.

needles and stem area are complex. The photosynthetic capacity of coniferous needles is distributed at a certain height, so the lower needles cause an increase in *LAI*. Finally, it should be mentioned that aggregated effects occurred in branches, which itself is a complex process. In light of these considerations, it is suggested that the hemispheric photo method should be combined with TRAC. The real *LAI* can be estimated by the concentration index obtained from TRAC.

6 Conclusions

The seasonal dynamics of *LAI* and canopy openness in DBF are more obvious than those in LF. Some trees in LF were infected by insect pests during the observation period, which caused some leaves to fall early. That may be one of the reasons why the variations of *LAI* and canopy openness in the LF are not as clear as those in DBF. PF consists of evergreen trees, so *LAI* and canopy openness in this community varied slightly over the whole year. In all the three forest communities, the trend of *LAI* is opposite to that of canopy openness.

Although no observations were conducted in October, the *LAI* in this month can be calculated from the dynamic seasonal curves. The estimated values are basically the same as the measurement results conducted in DBF and PF in October, 2002 by Liu et al. (2005).

Canopy uniformities of the two plantations, PF and LF, are higher than that of DBF, which is one of the results of fixed spacing in the planting method and regular growth in plantations.

The relations between *LAI* and canopy openness in the three forest communities show that canopy openness decreases with an increase of *LAI*. The two indices have a negative exponential relationship. Future studies ought to focus on the relationship between canopy openness and *LAI*, with the aim to verify the *LAI* by canopy openness.

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