Quantification of Spatial Structure Characteristics of Typical Natural Secondary Forest Gaps in Northeastern China

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Research

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Abstract

Background: To understand the theory of forest cycle and reveal the relationship between forest gaps and forest structure, species composition and biodiversity, we need to study the spatial structure of forest gaps. However, the complexity of natural secondary forest structure makes it difficult to quantify the spatial structure characteristics of gaps in large areas by field measurement. In this study, aerial orthophotos, and light detection and ranging (LiDAR), were used as data sources. The experimental area was Maoer Mountain Forest Farm, a typical natural secondary forest in northeastern China, and we used the investigation data of forest resources as reference material. We extracted 1343 forest gaps by manual digitization combined with canopy height model correction. The spatial characteristics of the extracted gaps were quantified from the spatial characteristics (area, shape complexity index), spatial heterogeneity (gap height diversity index) and spatial distribution characteristics (Clark–Evans index) of individual gaps.

Results: In the three types of natural secondary forest, the frequency distribution of gap area showed a negative exponential distribution: 90% of the gap area was less than 100 m^2. As forests aged, the proportion of gap area decreased from young forest to near-mature forest, and increased from near-mature forest to over-mature forest. The maximum frequency range of shape index changed from 1.2 to 1.4 for young forest, middle age forest and near-mature forest; and which is from 1.4 to 1.6 for mature forest and over-mature forest. The gap height diversity index increased from young forest to near-mature forest, decreased when the forest was mature and increased when it was over-mature. The spatial pattern of forest gaps was mainly random. The proportion of random distribution increased from young forest to middle-aged forest, decreased from near-mature forest to mature forest and increased from over-mature forest.

Conclusions: Most of the gaps in the natural secondary forest were small and medium-sized; the shapes were complex; the internal spatial heterogeneity was high; and the gaps were mostly randomly distributed. Use of aerial orthophoto and canopy height model sets was efficient and reliable in quantifying the spatial characteristics of forest gaps, and can replace the time-consuming (and usually field-based) measurement of their subjective spatial characteristics.

Background

Forest gaps are areas where forest communities are disturbed by natural or man-made factors, resulting in the death of one or more trees, and will be occupied and renewed by new individuals (St-Onge et al. 2014). The gaps provide favorable microenvironments for forest regeneration, and they play an important role in the regeneration and succession of natural secondary forest. Their size and frequency affect the species composition of forests (Runkle 1982; Brocaw 1987; Qinghong et al. 1991).The shape of forest gaps is closely related to the high diversity of vegetation within them for wildlife habitats (Patton 1975; Covich 1976; Marcot et al. 1983). Because of the diversity of gap spatial characteristics, the impact of gap species and the importance of environmental heterogeneity have attracted much attention (Putz

1983). The quantification of the spatial characteristics of forest gaps is of guiding significance for the study of forest ecosystems.

Traditional forest gap investigation is mostly carried out at the sample level, and the results of the investigation are obtained from field survey data and then extended to a wider range (Brocaw et al. 1991). There are some limitations to traditional methods: for example, it is not easy to obtain data when the sample area is large, and there are significant differences in the estimation of gap size using different field survey methods (Lima 2005).Compared with manual interpretation (which needs extensive field verification and experience) remote sensing is an efficient and accurate automatic gap recognition technology. Remote sensing data with medium spatial resolution can identify large forest gaps, but not small forest gaps (less than 30 m^2) (Asner et al. 2004; Negrón-Juárez et al. 2011; Clark et al. 2004). The emergence of high spatial resolution remote sensing data (IKONOS, Wordview, etc.) has solved this problem (He et al. 2009; Malahlela et al. 2014). Runkle (1992) discovered the potential of aerial photography in drawing forest gaps, and in subsequent studies Fox et al. (2000) compared the accuracy of the forest gap map generated by ground measurement with that of the high spatial resolution (1:15000) aerial image interpreted manually. Although aerial image interpretations can provide more general detection and mapping, they cannot provide the same detailed information about vegetation characteristics in forest gaps as field measurements (Fox et al. 2000). LiDAR technology has become widely used bacause forest information could be acquired effectively. Airborne laser scanning (ALS) data can measure the three-dimensional distribution of vegetation in the canopy (Lefsky et al. 1999), refine the terrain characteristics under the canopy to below the meter level (Reutebuch et al. 2003; Hansen 2015) and estimate the height of a large area of land and the height of forest canopy with the same accuracy (Anderson et al. 2006). LiDAR data have been applied to forest gap recognition (Vepakomma et al. 2008; Gaulton et al.2010; Mao and Hou 2019) and ALS data can achieve high accuracy and detailed gap characteristics (White et al.2018).

Quantification is the basis of characterizing the spatial structure of forest gaps. We can start with the size, shape and spatial distribution pattern of forest gaps, and the high diversity of vegetation in forest gaps. Area is often used to describe the gap size. It has been found that the gap area of coastal natural temperate rainforest follows the power zeta distribution (White et al. 2018) and the gap area of natural secondary forest follows the exponential distribution (Vepakomma et al. 2008). The gap area of mangrove forest in an American Everglades park also follows index distribution (Zhang 2008). The perimeter area ratio (P/A) and gap shape complexity index (GSCI) are used to describe the shape of the forest gap. The Shannon diversity index is used as the gap height diversity (GHD) index to describe the height diversity of vegetation in the gap. The shape of the forest gaps in secondary broad-leaved deciduous forest is very complex and has nothing to do with the size of the area. The vegetation diversity index in the forest gaps follows a normal distribution (Koukoulas et al. 2004). In past studies, the K function (Ripley 1976, 1977) was used to test the spatial pattern in forest gap distribution, and it was found that the distribution of mangrove forest gaps in an American Everglades park was random (Zhang 2008). These quantitative studies into gap characteristics mainly used the field measurement method.

This made it difficult to obtain a large number of gap samples, and it was also difficult to ensure the accuracy of gap measurement, especially for natural secondary forest with a complex structure. An efficient and reliable method is needed, to replace one that is time-consuming and whose accuracy is difficult to ensure.

Natural secondary forest is the main forest resource in China, especially in the northeast of the country. Early large-scale cutting of natural forest led to gradual degeneration of the main part of the forest resources into natural secondary forest. There are many kinds of natural secondary forests, and these are widely distributed. They provide abundant wood, firewood, forest by-products and other important resources for social and economic development, and play an important role in maintaining global ecological security and ecological balance. The ecological structure of natural secondary forest is relatively complex, and it is necessary to quantify the characteristics of the spatial structure of the gaps. This study used the canopy height model (CHM) extracted from aerial orthophotos and LiDAR as the data source, and Maoer Mountain Forest Farm, a typical natural secondary forest in northeastern China, was used as the experimental area. The spatial characteristics of the extracted forest gaps were quantified at three levels: the spatial characteristics of a single gap, the spatial heterogeneity within the forest gaps and the spatial distribution characteristics between forest gaps. There were, therefore, three reasons for this study: (1) to quantify the spatial characteristics of natural secondary forest gaps (i.e. size, shape, vegetation height diversity and spatial pattern distribution); (2) to reveal the spatial laws of forest gaps between different natural secondary forests (i.e. area distribution characteristics, shape complexity distribution characteristics, vegetation height diversity index distribution characteristics, spatial distribution characteristics); and (3) to evaluate the applicability of the method based on aerial orthophotos and CHM quantitative forest gap structure features.

Methods

Research area

The research area is located in the Maoer Mountain Experimental Forest Farm in Shangzhi City, Heilongjiang province, China (45°15'–45°29' N, 127°23'–127°43' E), with a total area of 2.6×10^3 hm^2 (Fig. 1). The original forest in this area began to suffer serious damage during the construction of the Middle East Railway in 1906. Bald and barren hills, shrubs, swamps and damaged remnant communities were predominant in this area until 1949. After the founding of New China, all kinds of secondary forest communities recovered and developed naturally under the influence of reasonable management,, forming a typical natural secondary forest in the east of northeastern China. At the time of writing, a typical secondary forest has formed in this area. The forest types are hard broad-leaved forest, soft broad-leaved forest and mixed coniferous and broad-leaved forest. The main broad-leaved species include Mongolian Oak (*Quercus mongolica* Fisch), Aspen (*Populous davidiana* Dode) and Manchurian walnut (*Juglans mandshurica* Maxim).

Data

LiDAR data were acquired using a LiteMapper 5600 LiDAR system (Riegl, Horn, Austria), adopting an LMS-Q560 (Riegl, Horn, Austria) as the laser scanner and a Yun-10 aircraft (Harbin Aircraft Manufacturing Company, Haerbin, China) as the airborne platform. Data collections were made on 14 and 15 September 2015 (deciduous season). When collecting data, the weather is clear and cloudless, which has no impact on lidar data collection. The LiteMapper 5600 system integrates laser ranging, global positioning system (GPS) and inertial navigation system (INS), including a single narrow band laser and a receiving system. The working wavelength of the laser was 1550 nm, the divergence angle of the laser beam was 0.5 mrad the waveform data recording interval was 1ns. The flight altitude was 1.2km, and the single point density was about 2 point/m^2. After taking into account multiple echoes and repeated coverage, the maximum point cloud density was found to be more than 10 point/m^2 and the average point cloud density to be about 3.7 point/m^2. The spatial resolution of the digital orthophoto map (DOM) acquired by the CCD (Charge-Coupled Device) camera simultaneously is 20 cm.

Using the adaptive TIN model filtering of TerraScan software (Terrasolid, Heisinki, Finland), the original LiDAR point cloud data were divided into ground point cloud and non-ground point cloud. The ordinary Kriging interpolation method was used to interpolate the ground point cloud to generate the digital elevation model (DEM). The inverse distance weighting method was used to interpolate the first echo point to generate the digital surface model (DSM) (Guo et al. 2010). Compared with the measured elevation of the differential GPS, the obtained LiDAR data has an elevation accuracy better than 0.3 m and a plane accuracy better than 0.5 m. The CHM was obtained from the reduction of DSM and DEM data (Fig. 2). The spatial resolution was 1 m, and the data were the floating point type (32 bits). DOM and CHM data were in TIFF format, using the Xi’an 80 geographic coordinate system and Gauss Kruger 3-degree belt projection coordinate system.

Gap extraction

According to Katarzyna et al. (2016), forest gaps are defined as areas with a height of less than 3m and an area of 5-1000 m^2 on the ground. Because the difference between the inner microenvironment of less than 5 m^2 and that of under forest is not significant, the inner microenvironment of more than 1000 m^2 is similar to that of open space. We adopted a stratified sampling method to select the complete age groups; that is, the types of stand included young forest, middle-aged forest, near-mature forest, mature forest and over-mature forest. There were 75 sub-compartments (Table 1): stands of Aspen (7 sub-compartments), and stands of mixed forest with Mongolian Oak (41 sub-compartments) and Manchurian walnut (27 sub-compartments) as the main tree species. We used aerial images of the 75 sub-compartments as the base map, and manual digitization method was used to extract forest gaps. The area of each gap (m^2) was calculated, and gaps less than 5 m^2 and greater than 1000 m^2 were excluded. ArcMap10.5 software (Redlands, California, America) was used to extract the grid with height of 0-3 m from CHM data and transformed it into vector graphics. Gap polygons were obtained and the geometric data were calculated as the basic parameters for quantification.1343 forest gaps of three forest types (Aspen, Mongolian Oak and Manchurian walnut) were extracted as sample of spatial feature quantification. This study did not adopt the method of full-automatic forest gap recognition, mainly because it is difficult to ensure the accuracy of the area and position of the forest gap needed for the quantification of the spatial characteristics of the forest gap, and there will be a lot of missing errors (Malahlela et al. 2014; Bonnet et al. 2015).

Quantitative method for analyzing spatial characteristics of forest gaps

Spatial characteristics of a single gap

The spatial characteristics of a single gap are quantified by three parameters: the size and shape of the gap and the spatial heterogeneity within the gap (Denslow et al. 1990; Runkle 1991). In this study, the area (m^2) and GSCI of a single gap were used to quantify the size and shape of the gap, respectively (Blackburn and Milton 1996). The method of calculating GSCI is shown in Formula 1. The shape complexity index value of a perfectly circular gap is 1. The more complex the shape of the gap is, the higher the value of the shape complexity index is. The spatial heterogeneity in forest gaps is quantified by the GHD index. The Shannon Formula (Formula 2) is used to calculate the GHD in forest gaps (Zenner and Hibbs 2000). In this study, we used Arcmap10.5 software (Redlands, California, America) to reclassify the CHM grids corresponding to forest gaps; that is [0,0.5], (0.5,1], (1,1.5], (1.5,2], (2,2.5], (2.5,3]. The percentage of the number of grids at six height levels was obtained, and the GHD index was calculated to quantify the height diversity of vegetation in the forest gaps (Formulas 1 and 2):

$$GSCI = \frac{P}{2\sqrt{A \times \pi}} \qquad (1)$$

$$GHD = -\sum_{i=1}^{N} P_i \ln P_i \qquad (2)$$

where *P* is the perimeter of a single forest gap, *A* is the area of a single forest gap, is the proportion of grid elements in the i-th height class and *N* is the number of grades into which the data are divided.

Quantification of spatial characteristics between forest gaps

The spatial distribution of forest gaps is the spatial distribution pattern of forest gaps. The boundary of sub-compartments in the study area was irregular. If K function (Ripley 1976, 1977) is used to quantify the pattern distribution, complex calculation will be produced. So in this study, a modified nearest neighbor index method, Clark–Evans (CE), proposed by Fidner (1995), was used to quantify the spatial distribution pattern of forest gaps. The CE index was obtained by dividing the average distance between the center of mass of each gap and its nearest neighbor with the expected value when the individuals in the forest gaps were randomly distributed (Formula 3). When CE = 1, it was considered that the forest gaps were randomly distributed. When CE < 1, distribution was clustered; and, when CE > 1, the gaps were evenly distributed. The deviation degree of and was tested by a normal distribution test. When the test was not significant (|u| < 1.96) (Formula 4), it was considered that the forest gaps in the sub-compartments were randomly distributed (Kint et al. 2000):

$$CE = \frac{r_A}{r_E} = \frac{\frac{1}{N}\sum_{i=1}^{N} r_i}{0.5\sqrt{\frac{A}{N}+\frac{0.0514P}{N}+\frac{0.04P}{N^{\frac{3}{2}}}}} \tag{3}$$

$$u = \frac{r_A - r_E}{\frac{0.26136}{\sqrt{N^2/A}}} \tag{4}$$

where *CE* is the Clark–Evans index, is the distance between the ith individual and the nearest neighbor; *N* is the number of forest gaps in the sub-compartments, *A* is the area of the sub-compartments and *P* is the perimeter of the sub-compartments.

Analysis method

Through the study of frequency distribution, the overall distribution of gap area, GSCI and GHD in the study area was obtained, and the correlation between area and GSCI, area and GHD was obtained by correlation analysis. One-way ANOVA was used to test whether there were significant differences in gap characteristics among three forest types (Aspen, Mongolian Oak and Manchurian walnut) and five age groups (young forest, middle-aged forest, near-mature forest, mature forest and over-mature forest). All analyses were realized by MATLAB R2019a software (Natick, Massachusetts, America).

Results

Gap area distribution

The percentages of gap area of stands of Aspen, Mongolian Oak and Manchurian walnut were 0.82%, 0.90% and 0.64%, respectively, none of the three amounted to 1%. This showed that, in the past, standing forests were not felled. The minimum gap area of all three standing forests was 5 m^2, and the maximum value was 946 m^2; this appeared in the Mongolian Oak stand. The average gap area of the three species was 30 m^2. The forest gaps with area less than 100 m^2 account for more than 90% (Table 2), indicating that the forest gaps in the three forest types were mainly small and medium in size (< 100 m^2), and the gap areas were less than or equal to the size of a mature crown (less than 100 m^2). The percentage of gap area in the stand area was: over-mature forest (1.14%) > young forest (0.89%) > middle-aged forest (0.89%) > mature forest (0.66%) > near-mature forest (0.40%). The proportion of gap area decreased from young to near maturity to over-maturity, consistent with the growth cycle of trees. The frequency distribution of gap areas of the three stands all accorded with the negative exponential distribution (Fig. 3).

Gap shape complexity distribution

The GSCI value of the circle is 1 and the GSCI value of the square is about 1.128 (complexity is 13%). When taking into account the preservation of the square angle of the grid format in the process of vectorization, the GSCI of a single gap should be equal to or greater than 1.128 in all the extracted gap polygons, $GSCI_{min}$ = 1.13, $GSCI_{mean}$ = 1.60 and $GSCI_{max}$ = 4.30. The variance in GSCI of gaps with an area of 5~50 m^2 was 0.05; the variance in GSCI of gaps with an area of 50~100m^2 was 0.12; and the variance in GSCI of gaps above 100 m^2 was 0.33. The frequency distribution of GSCI (Fig. 4a) was neither normal nor exponential. The correlation coefficient (p = 0.96) between gap area and girth circumference was extremely strongly positively correlated, and the correlation coefficient (p = 0.71) between gap area and GSCI was strongly positively correlated.

The mean values of the shape complexity index of gaps in the three types of forest (Aspen, *Q.mongolica* and *Manchurian walnut*) were all around 1.60, the maximum values were about 4 and the minimum values were close to 1.128. One-way ANOVA indicated no significant difference between the three (p > 0.05). According to the age group (Fig. 5), the maximum frequency of GSCI in the young, middle-aged and near-mature forest appeared in the interval of [1.2,1.4].The maximum frequency of GSCI in mature forest and over-mature forest appeared in the interval of [1.4,1.6] and the percentage of this interval was even greater (> 30%). GSCI had a strong positive correlation with the gap area: the larger the gap area, the more complex the gap shape. The maximum frequency in the complexity index of forest gaps increased from 1.2-1.4 to 1.4-1.6. The higher the stand age, the more complicated the gap shape was.

The distribution of vegetation height diversity in forest gaps

The distribution of vegetation height in forest gaps is mostly high on the edge and low in the inner part. There are vegetation with measurable height in some gaps (Fig. 6). The frequency distribution of the GHD index is shown in Fig. 7(a). Figure 7(b) shows that there is a weak correlation between gap area and height diversity (p = 0.2996), but that when the area is large (> 200m^2), the GHD index is generally at a medium to high level. When the area is small (< 100m^2), there are forest gaps with a low diversity index.

The GHD mean of Aspen stands (1.14) was 12% and 10% lower than those of mixed forest with Mongolian Oak stands (1.28) as the main tree species and those of Manchurian walnut stands (1.30) as the main tree species. One-way ANOVA revealed that there were significant differences in GHD between single-species Aspen forest and the two mixed forests (Aspen stand–Mongolian Oak stand: P = 9.998e-05; Aspen stand–Manchurian walnut stand: P = 0.002). There was no significant difference between the two mixed forests (Mongolian Oak stand–Manchurian walnut stand: P = 0.2503).

The GHD mean values of the forest gaps in the over-mature and near-mature forests were 8%, 6% and 9% higher than those in the young, middle-aged and mature forests, respectively (Fig. 8). The forest gaps in the forest at approximately GHD = 1.5 were relatively high (over-mature forest > near-mature forest > middle-aged forest > mature forest > young forest). One-way ANOVA revealed no significant difference between the over-mature forest and the near-mature forest (P = 0.749). However, there were significant differences between the GHD in the forest gaps of other age groups (P<0.05), for example, over-mature forest *v.s.* young forest (P = 0.0004); over-mature forest *v.s.* middle-aged age forest (P = 0.0102); over-mature forest *v.s.* mature forest (P = 0.00004); near-mature forest *v.s.* young forest (P = 0.0101); near-mature forest *v.s.* mature forest (P = 0.005).

Spatial distribution pattern of forest gaps

Of the 75 sub-compartments, eight (one Aspen stand, six Mongolian Oak stands and one Manchurian walnut stand) had only one forest gap or no forest gaps. CE values can be obtained in other sub-compartments and normal distribution test is carried out. These tests were not significant: 65% had a random distribution, 25% had an aggregated distribution and 10% had a uniform distribution (Fig. 9). The pattern of distribution in the sub-compartments with different tree compositions was similar: random distribution was over 50%, aggregated distribution was less than 40% and uniform distribution was below 20% (Fig. 10a). In the sub-compartment divided by different age groups (Fig. 10b) there was a periodical change in the spatial pattern distribution of forest gaps. As stand ages increased, the proportion with random distribution in sub-compartments first increased and then decreased, and the proportion with aggregated distribution in sub-compartments first decreased and then increased. Uniform distribution presented a trend of first increasing and then decreasing.

Discussion

Analysis of gap area law

The gap size will affect factors such as light intensity and soil moisture, which will then influence the regeneration effect (Muscolo et al. 2014) and growth response (Stan and Daniels 2014). Studies have been carried out into the frequency distribution of gaps in tropical and subtropical forests (e.g. Fisher et al. 2008; Lloyd et al. 2009; Kellner and Asner 2009; Boyd et al. 2013; Asner et al. 2013) but, to the best of our knowledge, there are no studies of the law of change in the gap area of natural secondary forests (Vepakomma et al. 2008). The gap size and frequency distribution used in this study provides an effective single indicator for use in the comparison between and within different forest ecosystems (Andrew et al. 2016). The frequency distribution of the gap size of the three tree species all conforms to the negative exponential form, which is consistent with the size and frequency distribution of the mangrove gap (Zhang 2008). This shows that small and medium-sized forest gaps are the most common in natural secondary forests. On the one hand, due to the good protection of the study area, less human and natural interference, there is no large area of forest gap. On the other hand, the regeneration speed of young trees in natural secondary forest is fast, and the water and heat conditions of large gaps are better than those of small gaps, which leads to the rapid reduction of gap area. This also reflects the fact that the three forest stands in the study area were relatively stable. A comparison of the size of the gaps in these stands revealed that the average and median gap areas in the Aspen stand were smaller than those in the two mixed forests. This was mainly due to the complicated environment of mixed forests, which led to a large gap between tall trees; in addition, the gap area formed after any disturbance was larger than that in single-species forests.

The age group is an age-level rectification, which accords with the different stages in tree growth in the forest. According to the length of the growth cycles, the forest ages corresponding to the age groups of fast-growing tree species, meso-growing tree species and slow-growing tree species are different, but the growth stages are the same. Limited by the number and size of plots, there was no gap between the near-mature single-species forest of Aspen and the young mixed forest with Mongolian Oak as the main tree species. This was caused by the accident of a single sample, and the forest gaps of 3 types of forest stands: there was no significant difference between them ($P > 0.05$). Observed from different age groups, during the period of young and middle-aged forests, the growth rate of trees in the stands is relatively slow, and it is susceptible to external interference to form forest gaps. At this time, the gap area accounts for a large proportion. As the trees mature and grow faster, the proportion of forest gaps in the near-mature forests is significantly reduced. The trees grow slowly after maturity and the ability to resist interference decreases; and, because the canopy width reaches its maximum (hindering the regeneration of young trees beneath it), the proportion of the gap area gradually increases. Eventually, as forest stands grow, the proportion of gap areas first decreases and then increases, consistent with the growth cycle in a natural secondary forest.

Analysis of the law of complexity of gap shape

The mean value of shape complexity index ($GSCI_{mean}$ = 1.6048) is nearly five times more complicated than that of squares (60.48/12.8), and the maximum value (60.48/12.8) is 25 times more complicated than that of squares (325.92/12.8). The GSCI (White et al.2018) in temperate coastal rainforests in Canada is between 1.5 and 1.7, and the gap complexity index of semi-natural secondary forest gaps in the southern UK (Koukoulas et al. 2004) is between 1.1 and 2.64. In contrast, the shape complexity index of natural secondary forest gaps is higher and more complicated. It is assumed that the canopy of the trees in the stand is regular, and the small gap caused by one absent tree should be square on the CHM (GSCI $\approx$ 1.128), so the shape complexity index should be low. In addition, natural disasters such as fires and strong winds will cause a large area of canopy to be lost, and the shape complexity index will also be low. Therefore, the gaps with high shape complexity index can be understood as the gaps with complicated shape formed by multiple trees falling down, or the regular gaps are caused by the growth of side branches of boundary trees. The forest gaps of natural secondary forests have similar shapes (i.e. approximate GSCI values). However, it can also be seen that larger forest gaps tend to have a larger range of shapes, while the variability of smaller forest gaps is greatly reduced. The shape of this small gap approximates to that of a circle. , and this consistency indicates that it is caused by the lodging of a single tree.

Analysis of vegetation height diversity in the forest gap

In this study, the Kolmogorov–Smirnov test confirmed that the GHD index did not follow a normal distribution, and this differs from previous research results (Koukoulas et al. 2004). The frequency of the forest GHD index in the study area increased with the height diversity index, indicating that height heterogeneity in most forest gaps in natural secondary forests was high. This was believed to be due to the rapid growth of natural secondary forests. The sufficient light inside the gap makes the intolerant tree species grow rapidly, resulting in a high degree of heterogeneity. In comparison, the understory environment in mixed forests was more complicated than in single-species forests, and the forest gaps in mixed forests often had more understory vegetation (including shrubs and grasses), so the height diversity index was higher. The near-mature forest and over-mature forest were significantly different from other age groups. The former had an higher average high diversity index value, indicating that the vegetation in the gap was more abundant than in the young, middle-aged and mature forests. The periodic change in vegetation diversity in the gap was caused by the regeneration of vegetation in the gap.

Analysis of spatial pattern distribution of forest gaps

The spatial pattern of distribution of gaps in forest stands can inform speculation on the mechanism of gap formation, and promote understanding of the pattern of forest turnover (Zhang 2008). In the study area, the forest gaps were mostly distributed randomly, followed by aggregate distribution; uniform distribution was the rarest. Sub-compartments that appeared to be evenly distributed were all areas with few forest gaps. The forest gaps in the mangroves of the Everglades National Park in the USA are randomly distributed (Zhang 2008), and the results shown in this study are similar. The position of randomly distributed gaps in sub-compartments is more scattered, which can promote the regeneration of stands in sub-compartments to a greater extent. In contrast, clustered forest gaps are more concentrated in the sub-compartments. Their impact is local (smaller) and also affects regeneration of the forest stands. Most of the forest gaps in natural secondary forests are randomly distributed, and this can promote their natural regeneration, change the composition of tree species and increase the proportion of non-shade-tolerant pioneer tree species, thus enriching the tree diversity in these forests.

Extraction and quantification of forest gaps

Forest gaps are considered to be local and discrete, and not part of an “open” system (White et al., 2018). The formation of forest gaps, and their changes in space and time, are worthy of attention (Lertzman et al. 1996). At the landscape level, the spatial assessment of forest gaps is usually limited by the methods used to detect and map them (Schlieman and Bockheim 2011). The use of aerial orthophotos has potential, compared with the traditional time-consuming and laborious field measurement method (Runkle, 1992). Fox et al. (2000) compared the accuracy of the forest gaps produced by ground measurements with those produced by aerial orthophotos (1:15000) and found that the forest gap maps interpreted from aerial orthophotos were more accurate; the omission rate of aerial orthophotos was only 4.7%, while that of the ground survey was 25.6%. However, although aerial orthophoto interpretation can provide more basic information for gap detection and mapping, it cannot provide the same detailed information about vegetation characteristics within the gap as field measurements (Fox et al., 2000). Therefore, in this study, LiDAR data synchronized with aerial orthophotos was used to extract CHM to modify the forest gap extracted from aerial orthophotos, and to extract the forest gap height in order to quantify its characteristics. This method can provide a large number of more accurate gaps for the quantification of gap characteristics. In addition, time series aerial orthophotos and LiDAR data can quantify changes in the size and shape of the gap over time (Vepakomma et al., 2011).

Conclusion

The spatial characteristics of forest gaps have an important impact on forest renewal dynamics and species composition. However, it is difficult to measure the spatial characteristics of large spatial regions using field measurements. In this study we used remote sensing to quantify four aspects of the gap: size, shape index, diversity of vegetation height and spatial pattern distribution. This allowed us to characterize the spatial characteristics of individual forest gaps, the spatial heterogeneity within forest gaps and the distribution characteristics between forest gaps.

We found that, among the three natural secondary forest stands, the gap area was dominated by small and medium-sized forest gaps. The shape complexity and vegetation height diversity within the gaps were high. The spatial pattern was mostly random distribution, followed by aggregated distribution. The size of a single gap in the Aspen stand was smaller than that in mixed forests dominated by Mongolian Oak and Manchurian walnut, and the spatial heterogeneity within the gap was lower.

The shape and spatial heterogeneity of natural secondary forest gaps were found to be more complicated. The community structure of natural secondary forests is unstable, and subject to its own biological characteristics and external interference. As forest age increases, the size of a single gap in the forest stand, the height diversity index of vegetation in the gap and the spatial pattern distribution between gaps shows periodic changes. The composition of tree species has an effect on the size and spatial heterogeneity of individual gaps in the stands, and the growth rate of trees has an effect on the spatial pattern of gaps.

In this study, the quantification of forest gap spatial characteristics based on aerial orthophoto and CHM data is an efficient and reliable method, which can replace the time-consuming and usually on-site subjective measurement of forest gap characteristics.

Abbreviations

ALS: Airborne Laser Scanning; CE: Clark-Evans; CHM: Canopy Height Model; DEM: Digital Elevation Model; DOM: Digital Orthophoto Map; GHD: Gap Height Diversity; GPS: Global Positioning System; GSCI: Gap Shape Complexity Index; INS: Inertial Navigation System; LiDAR: Light Detection And Ranging.

Declarations

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Availability of data and materials

The datasets used and/or analyzed in this study are available from the corresponding author on request.

Authors' Contributions

Sifu Bi proposed the study, acquired the data, did the experiment of segmentation and classification for forest gaps based on object-oriented methods, interpreted the results and wrote the manuscript. Yifan Tan verified and analyzed the classification results and contributed in manuscript writing and revision. Yao Wang and Meiwei Liu verified and analyzed the classification results and contributed in manuscript writing and revision. Xuegang Mao advised on the study design, conducted the fieldwork, image processing and analysis, contributed to manuscript writing and revision. All the authors have read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1: Natural secondary stands of Aspen, Mongolian Oak, and Manchurian walnut.

Stand type	Age group	Number (a)	Altitude (m)	Canopy density	Number per hectare (strain /ha)	The measure of area (ha)
Aspen Stand	Young forest	3	288-370	0.8	1200-1800	7.32
	Middle- aged forest	1	344	0.6	3000	11.45
	Near- mature forest	1	410	0.7	1650	0.07
	Mature forest	1	410	0.5	900	2.53
	Over- mature forest	1	330	0.8	2000	11.48
Mongolian Oak Stand	Young forest	2	330-490	0.7-0.9	1020-1300	4.25
	Middle- aged forest	12	350-405	0.6	670-1200	34.62
	Near- mature forest	9	355-710	0.6-0.8	635-1450	70.22
	Mature forest	9	340-470	0.5-0.8	800-2200	61.00
	Over- mature forest	9	400-630	0.7-0.9	900-1600	103.54
Manchurian walnut Stand	Young forest	9	270-480	0.6-0.8	1000-1900	62.45
	Middle- aged forest	5	310-454	0.7-0.8	800-1900	24.59
	Near-mature forest	7	320-428	0.6-0.8	800-2400	50.26
	Mature forest	5	365-620	0.6-0.9	600-1110	74.77
	Over-mature forest	1	474	0.7	900	12.80

Table 2: Gap area statistics of three natural secondary forests of different age groups.

Stand type	Age group	Numbe of forest gaps	Gap area Mean / maximum （m^2）	Mean value of gap area (m^2)	Gap area variance	Percentage of gaps below 100 m^2 (%)	Number of gaps greater than 200 m^2
Aspen Stand	Young forest	20	50/716	13	24706	95	1
	Middle-aged forest	13	70/500	29	17488	92	1
	Near-mature forest	0	-	-	-	-	-
	Mature forest	47	12/60	7	144	100	0
	Over-mature forest	10	26/87	13	801	100	0
	Total	90	30/716	9	8282	98	2
Mongolian Oak Stand	Young forest	0	-	-	-	-	-
	Middle-aged forest	104	43/946	15	11282	92	5
	Near-mature forest	90	38/519	13	6014	92	4
	Mature forest	123	40/832	11	10801	94	5
	Over-mature forest	492	29/551	15	2354	95	10
	Total	809	34/946	14	5196	94	24
Manchurian walnut Stand	Young forest	179	31/690	12	4253	96	2
	Middle-aged forest	48	42/660	11	10787	94	3
	Near-mature	90	32/366	13	2870	93	2

	forest						
	Mature forest	123	38/486	12	4689	90	5
	Over-mature forest	4	8/13	6	14	100	0
	Total	444	34/690	12	3779	93	12

Figures

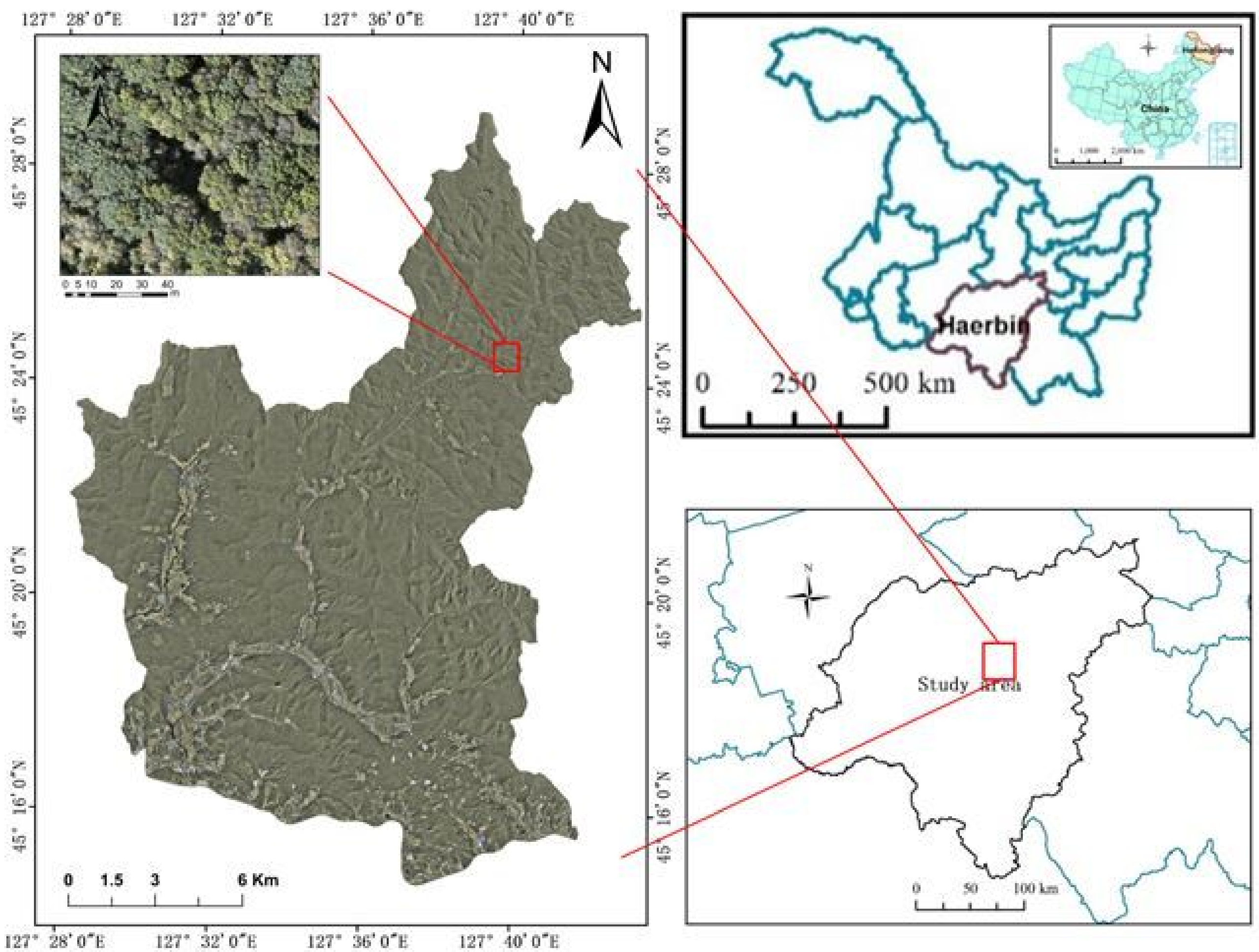

Figure 1

Study area location and aerial photographic data source. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

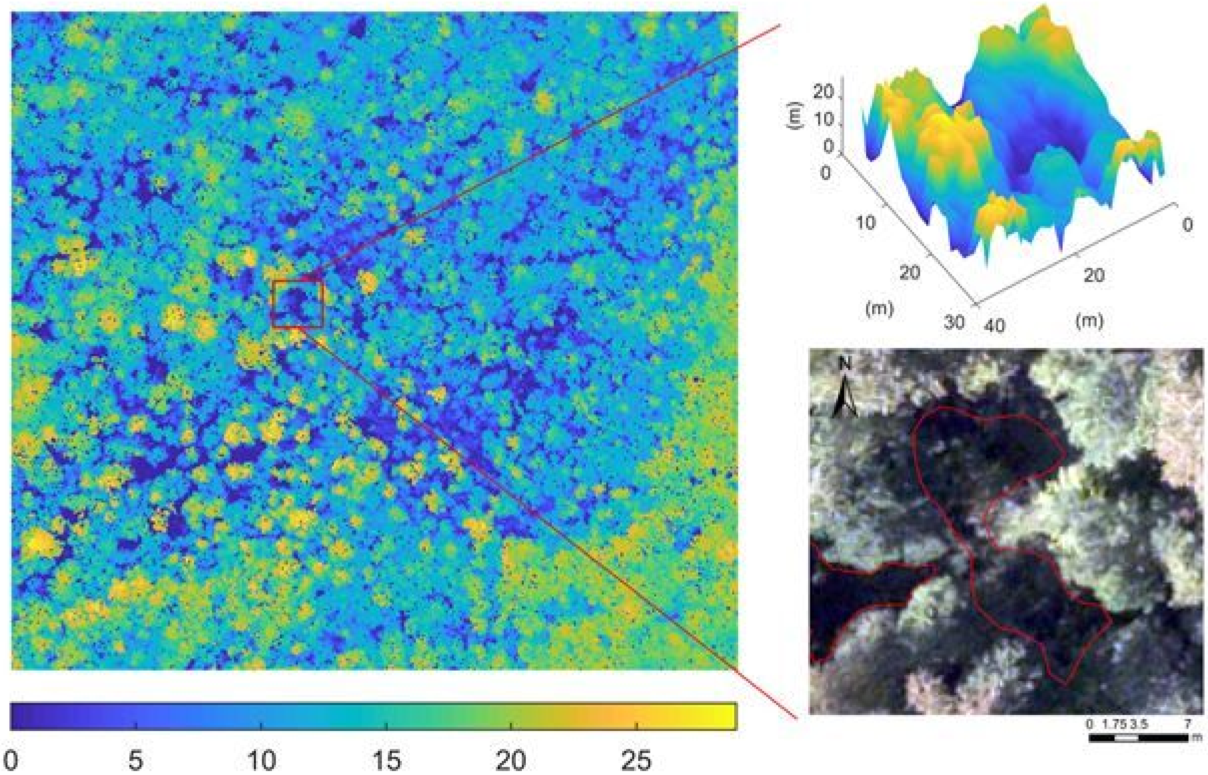

Figure 2

The gap in canopy height model (CHM)

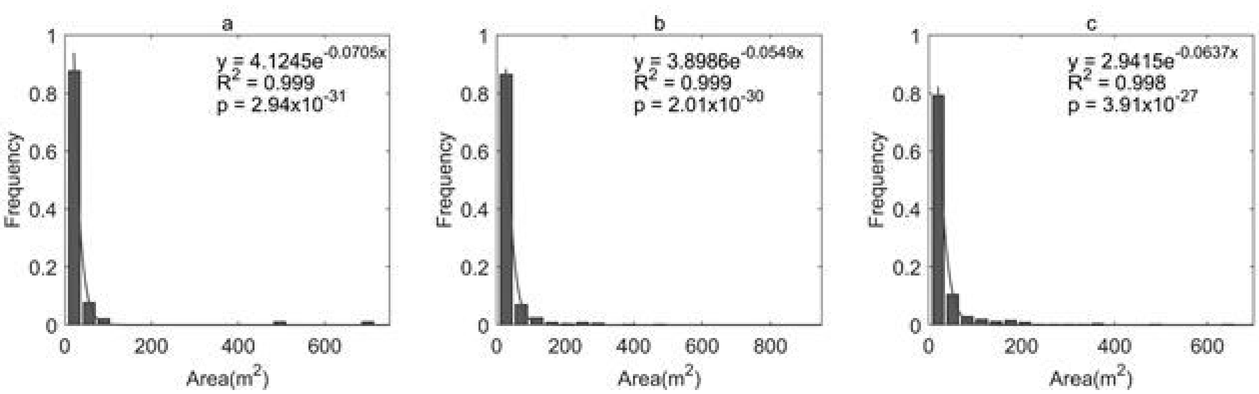

Figure 3

Histogram of gap area frequency distribution. (a, b and c were mainly species of Aspen, Mongolian Oak and Manchurian walnut, respectively.)

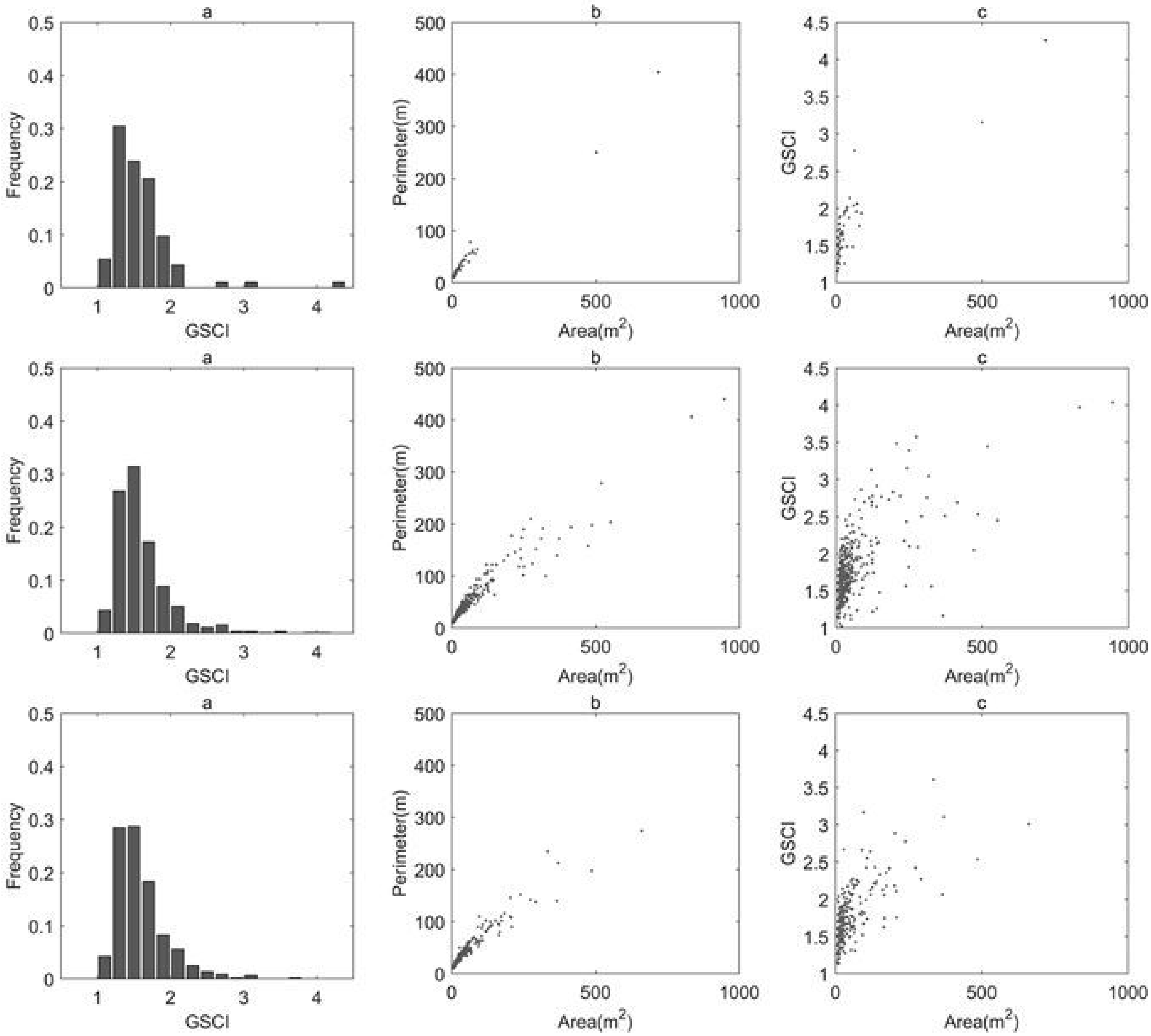

Figure 4

Frequency distribution histograms. GSCI; scatter diagram of perimeter (m) and GSCI; and scatter diagram of area(m2) and GSCI. (The main tree species were stands of Aspen in the first row, Mongolian Oak in the second row and Manchurian walnut in the third row.)

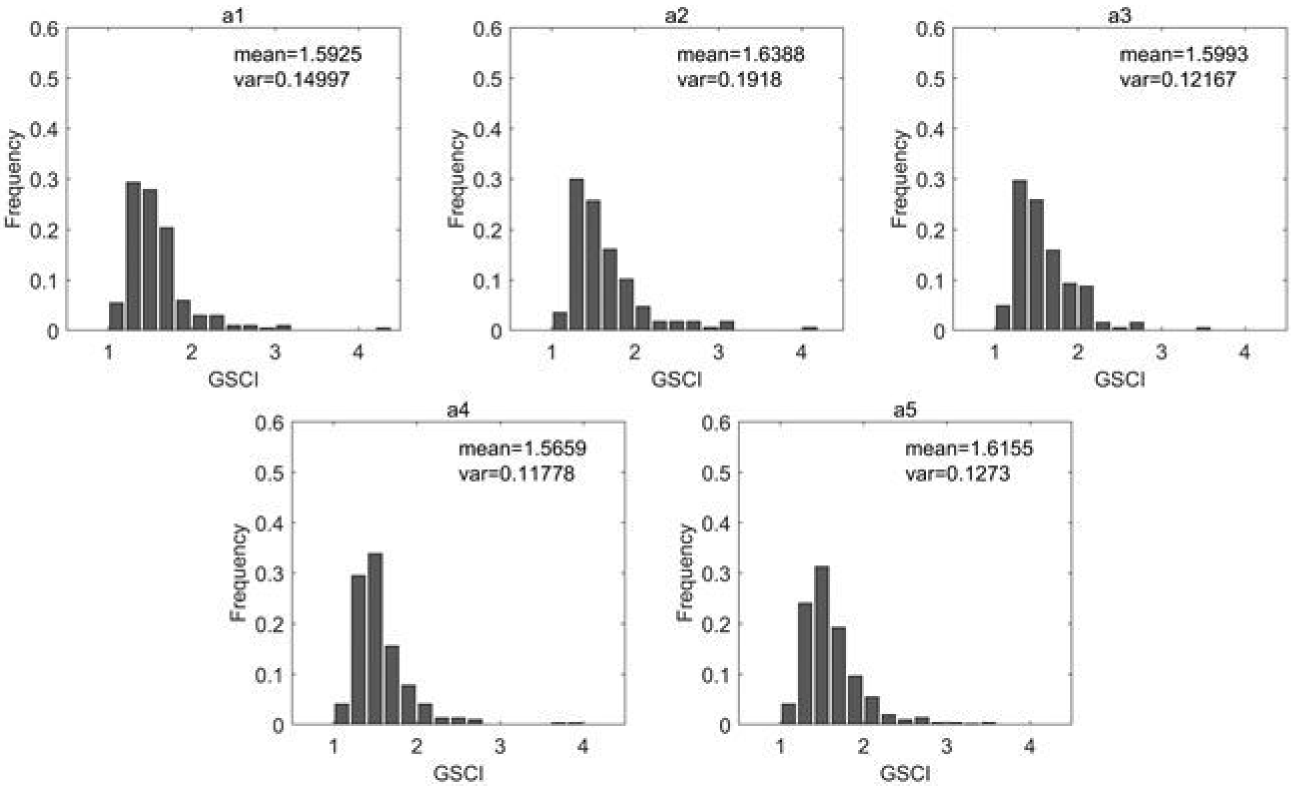

Figure 5

Frequency distribution histogram of GSCI of forest gaps in each age group. a1, a2, a3, a4 and a5 were young, middle-aged, near-mature, mature and over-mature forests, respectively.

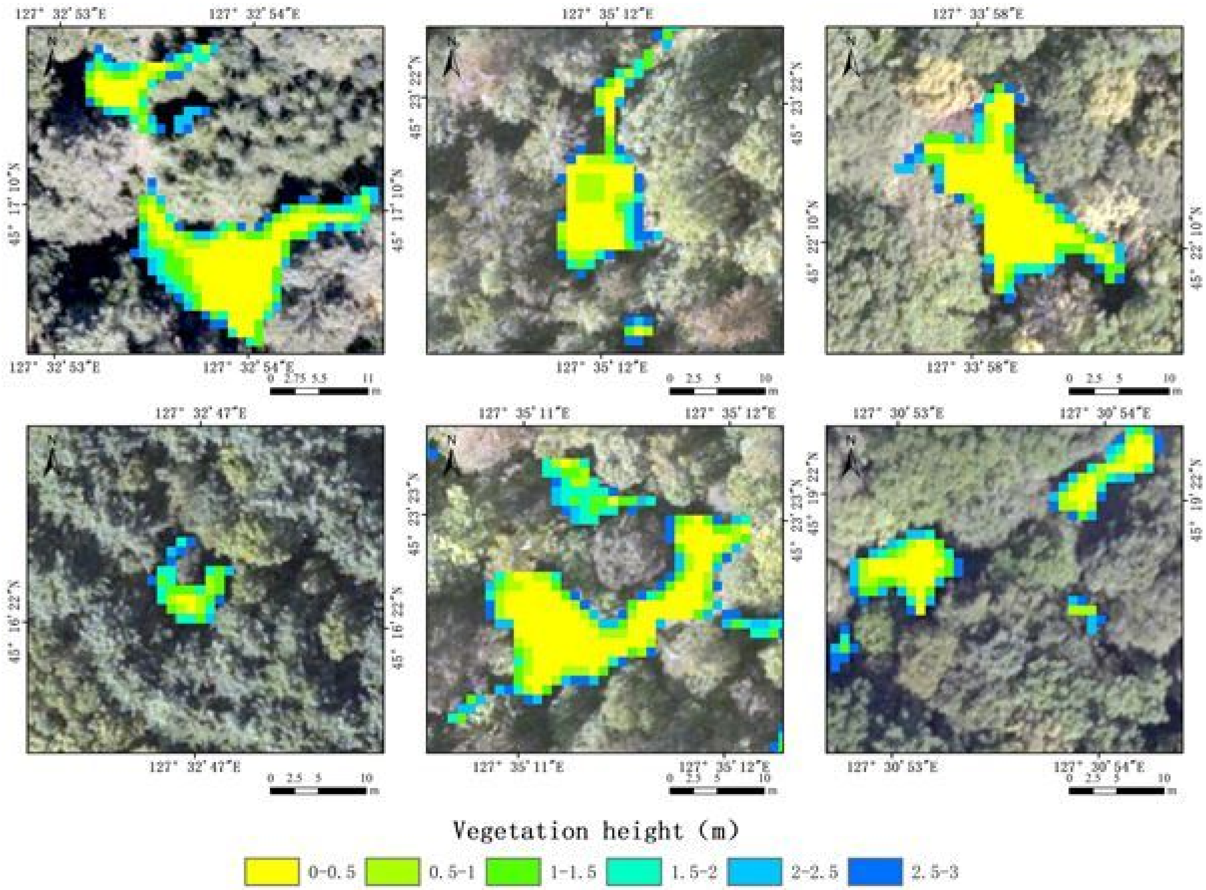

Figure 6

Examples of vegetation height distribution in forest gaps of three natural secondary forests.

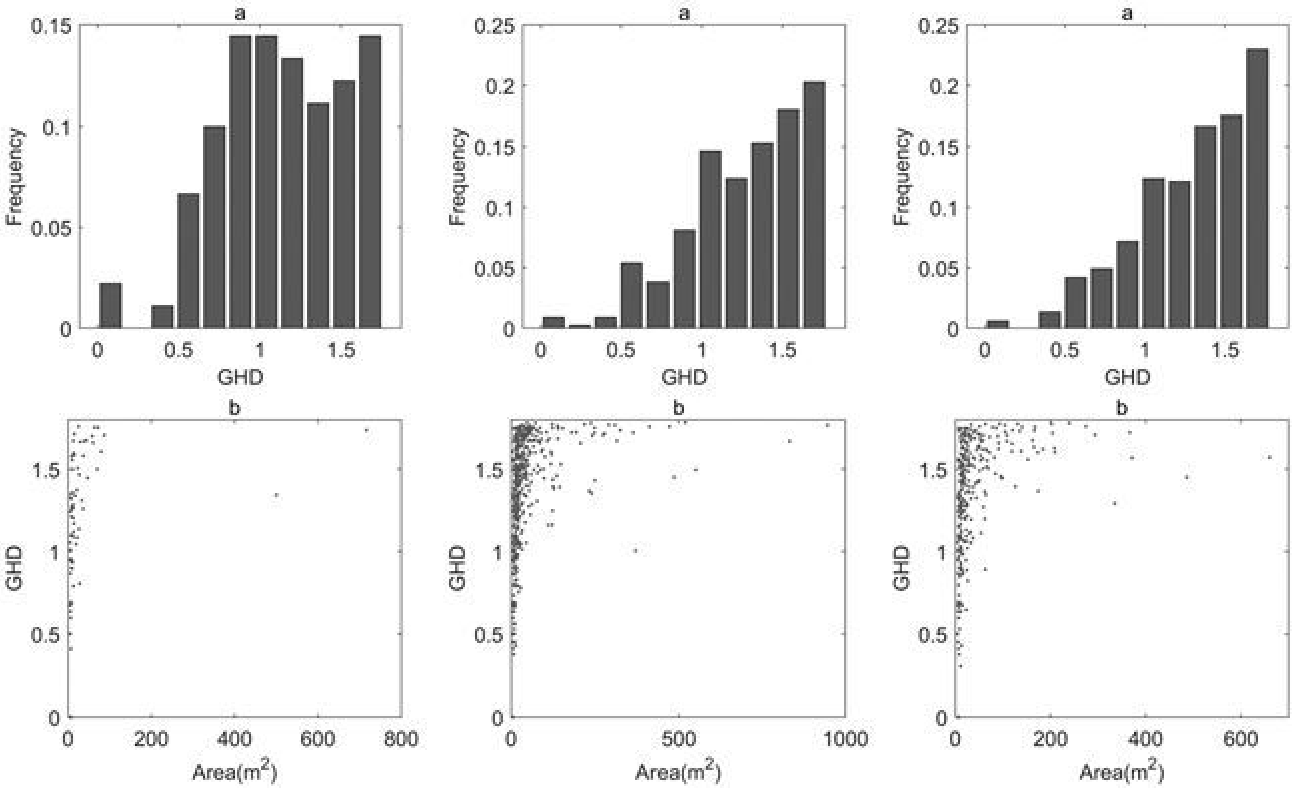

Figure 7

GHD frequency distribution histogram (a); scatter plot of gap area and high diversity index (b). (The main tree species were stands of Aspen in the first column, Mongolian Oak in the second column and Manchurian walnut in the third column.)

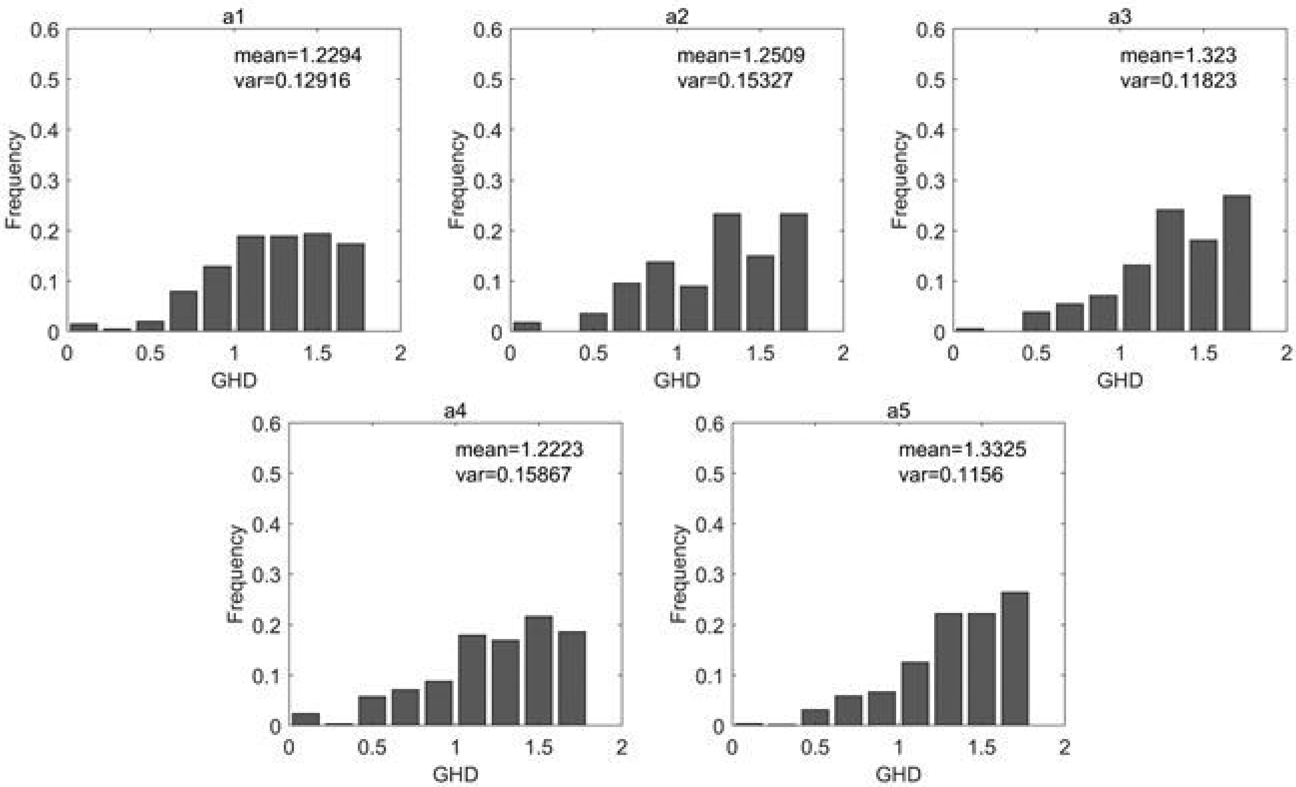

Figure 8

Histogram of GHD frequency distribution of forest gaps in each age group. a1, a2, a3, a4 and a5 were young, middle-aged, near-mature, mature and over-mature forests, respectively.

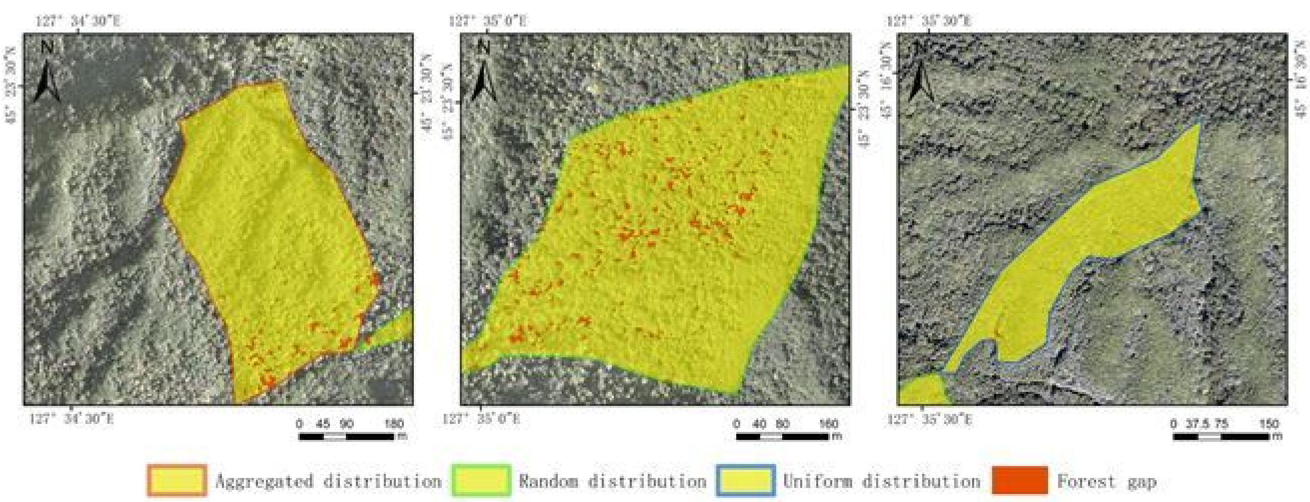

Figure 9

Spatial distribution pattern of forest gaps.

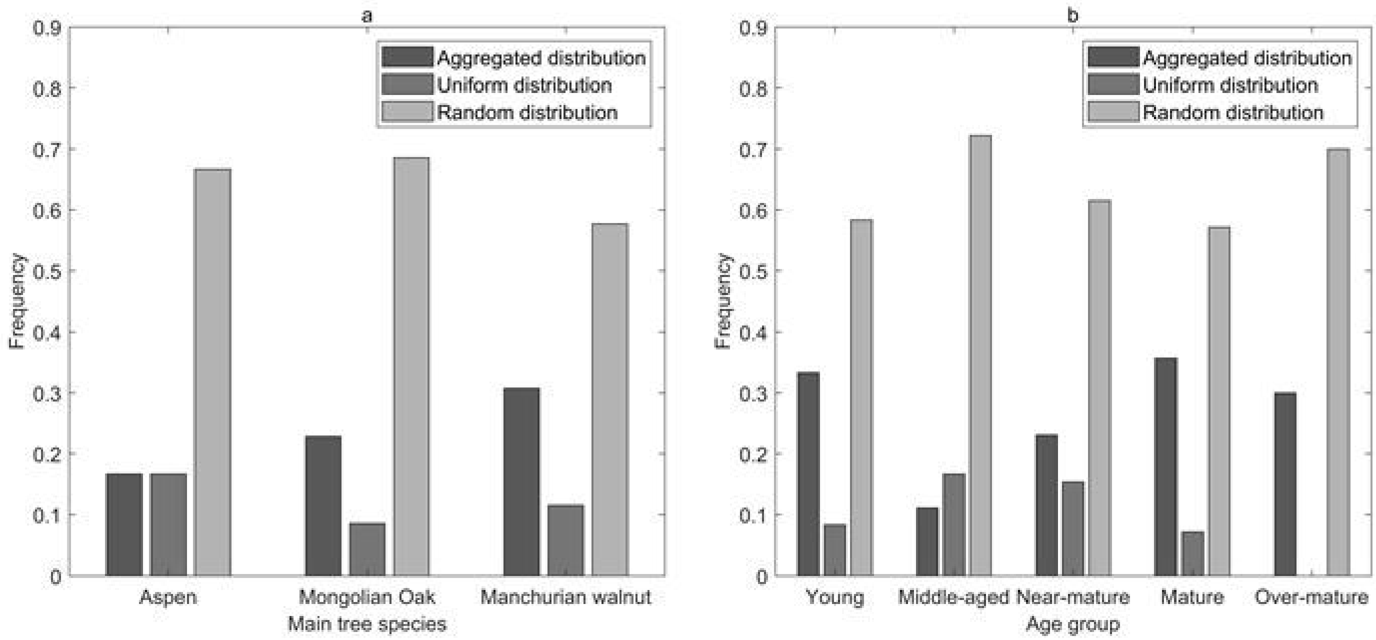

Figure 10

Distribution of spatial pattern of forest gaps in different species (a) and age groups (b).