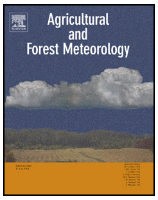
Agricultural and Forest Meteorology 213 (2015) 64–76

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



On the size of forest gaps: Can their lower and upper limits be objectively defined?

Jiaojun Zhu[a,*], Guangqi Zhang[d], G.Geoff Wang[b], Qiaoling Yan[a], Deliang Lu[d], Xiufen Li[c], Xiao Zheng[a]

[a] State Key Laboratory of Forest and Soil Ecology; Qingyuan Forest CERN, Chinese Academy of Sciences; Institute of Applied Ecology, Chinese Academy of Sciences (CAS), Shenyang 110016, China
[b] School of Agricultural, Forest and Environmental Sciences, Clemson University, Clemson, SC 29634-0317, USA
[c] Shenyang Agricultural University, Shenyang 110866, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 20 June 2015
Accepted 24 June 2015

Keywords:
Gap size
Gap threshold
Growing season
Light
Shadow length

ABSTRACT

Gap size is critically important to ecological processes that drive forest dynamics within the gap, yet its threshold has never been explicitly defined. Consequently, gap sizes reported in the literature ranged from 4 m^2 to 2 ha, which makes comparisons among and synthesis of the published gap studies difficult. We suggested that the lower size limit be defined by the mean shadow length (SL) of canopy trees surrounding the gap (CTSG) at local 12:00 during growing season (GS), while the upper size limit be defined by considering the farthest impact of CTSG on growth of shade intolerant tree species, which was determined by the mean of SL at the initial and the final times when 30-min photosynthetic active radiation (PAR) is more than the light saturation point for shade intolerant tree species each day during GS.

The lower and upper limits of expanded gaps (the canopy gap plus the area extending to the bases of the canopy trees surrounding the gap) represented by gap diameter: CTSG height ($R_{D/H}$) were 0.49 and 3.49, respectively, for temperate forest areas. The lower limit of gap size is determined only by the location and the height of CTSG, which should be applicable worldwide. We also tried to provide a universal method for determining the upper limit of gap size without applying the observed PAR data, and using only sunshine duration, an easily obtained variable from meteorological stations worldwide. We suggest that expanded gaps may be classified as: small gap, $0.49 < R_{D/H} \leq 1.0$, medium gap, $1.0 < R_{D/H} \leq 2.0$; large gap, $2.0 < R_{D/H} < 3.5$ in temperate forests.

1. Introduction

The opening of the canopy (forest gap) induced by the death of one or more trees (Runkle, 1982), plays a key role in regulating compositional and structural diversity (Hubbell et al., 1999; de Grandpre et al., 2011), nutrient cycling (Ediriweera et al., 2008), and regeneration and succession (Hu and Zhu, 2009; Schliemann and Bockheim, 2011) in forest ecosystems. Numerous studies have been conducted worldwide on forest gaps, covering their definitions (Watt, 1947; Brokaw, 1982; Gray and Spies, 1996), characteristics (Hu and Zhu, 2009; Sefidi et al., 2011), spatial patterns and temporal dynamics (Brokaw, 1982; Runkle, 1982; Elias and Dias, 2009; Garbarino et al., 2012), and studying effects of gaps on microclimate and regeneration process (Lawton and Putz, 1988; Quine, 2001; Arevalo and Fernandez-Palacios, 2007; Elias and Dias, 2009; Yan et al., 2010; Humber and Hermanutz, 2011). These studies have identified that gap size is the most important trait of a forest gap influencing microclimates (Zhu et al., 2014), regeneration (Gray and Spies, 1996), and succession (Schliemann and Bockheim, 2011).

Despite the critical importance of gap size, its lower and upper limits have never been explicitly defined. Currently, there are many inconsistencies among published studies with regard to gap size. A forest gap is commonly defined as either a "canopy gap", an opening in the forest canopy down through all foliage levels to an average regeneration height of 1 m (Myers et al., 2000) or 2 m (Brokaw, 1982), or an "expanded gap", the canopy gap plus the area extending to the bases of the canopy trees surrounding the gap (Runkle, 1982). Neither definition, however, is explicit about gap size. No

---

[*] Corresponding author. Fax: +86 24 83970300.
E-mail address: jiaojunzhu@iae.ac.cn (J. Zhu).

http://dx.doi.org/10.1016/j.agrformet.2015.06.015

lower limit for forest gaps has been defined, below which a small canopy opening is no longer ecologically distinctive enough to qualify as a forest gap. Similarly, no upper limit for forest gaps has been defined, above which a forest gap is ecologically indistinct from an open area.

To estimate the size of forest gaps, several methods have been developed in previous studies. Because forest gaps are often irregular shapes, gap size has been approximated by ellipsoidal shapes through fitting the gap length and width using an ellipse model (Runkle, 1982), by octagonal or sixteen-sided shapes through estimating gap size from a scale map drawn with eight (Brokaw, 1982) or sixteen (Green, 1996) coordinates of direction and distance from a convenient point near the gap center to the gap edge, or by triangular shapes through dividing a gap into triangles and measuring the sides of each triangle (de Lima, 2005). Zhu et al. (2009) presented an approach using elliptical sectors instead of polygons to calculate the gap size, which resulted in a more accurate estimate than the octagon method. In addition, hemispherical photographs have been used to estimate canopy gap sizes (ter Steege, 1993; Hu and Zhu, 2009). However, these methods were developed to calculate the area of an irregular forest gap, and none attempted to delimit the gap size.

A forest gap is essentially an area free of direct occupancy of mature trees but its environment is still affected somewhat by the surrounding forest matrix through the edge effect. Therefore, canopy trees surrounding a gap (CTSG) moderate the gap environment and regeneration process, and the ratio of gap diameter to the height of CTSG has been proposed as a surrogate measure of gap size (Gray and Spies, 1996; Schliemann and Bockheim, 2011). However, none of the previous studies explicitly defined the lower and upper limits of gap size based on the ratio. Consequently, gap size reported in the literature ranges from as small as 4 m^2 (Lawton and Putz, 1988; Kenderes et al., 2008) to as large as 2.0 ha (Shure et al., 2006) (Table A1).

Several studies attempted to define the lower and upper limits of gap size, but their proposed limits were largely arbitrary or qualitative in nature. Runkle (1992) implicitly defined the limits of gap size by the number of canopy trees that died during the gap formation, with the lower and upper limits corresponding to the death of one-half to 10 canopy trees. Some studies used arbitrary values, including 4 m^2 (Lawton and Putz, 1988), 10 m^2 (Nakashizuka et al., 1995), 20 m^2 (Brokaw, 1982), and 25 m^2 (Veblen, 1985) to define the lower limit of gap size. Other researchers set the lower limit with qualitative expressions such as “more than one whole canopy tree” or “the canopy opening was not obscured by the regeneration” (Runkle, 1992). A recent review on methods for studying forest gaps found that the gap size varied widely from 10 to >5000 m^2; 1000 m^2 was suggested as the maximum gap size because the openings larger than 1000 m^2 tend to have microclimates and return intervals significantly different from the smaller gaps (Schliemann and Bockheim, 2011).

One of the difficulties in determining the gap limits is that these limits may vary with the height of CTSG because CTSG influence the environmental conditions within the gaps, which, in turn, affect ecosystem processes such as regeneration and succession. Since taller CTSG would affect the environment over a larger area, the height of CTSG becomes an important factor that influences the gap size and must be considered when determining the gap limits. For example, when the mean height of CTSG is 30 m (Muscolo et al., 2010), a gap of 1000 m^2, defined as the upper limit of gap size by Schliemann and Bockheim (2011), resulted in a ratio of gap diameter to height of CTSG being only 1.2, which was classified as a medium-sized gap by Gray and Spies (1996). However, when the mean height of CTSG is 7 m (Zhu et al., 2003; Clarke, 2004), a gap of 1000 m^2 would result in the ratio of gap diameter to height of CTSG being 5.1, which should be defined as an open area instead of a gap.

Currently, the lack of ecologically defined limits on gap size has resulted in great inconsistencies among gap studies. These inconsistencies not only lead to confusion in gap definition and classification, but also make it difficult to compare results from different studies on forest gaps. Therefore, the objective of this study is to propose an approach that can be applied to objectively determine the lower and upper limits of gap size.

2. Materials and methods

2.1. Study area

This study was conducted at Jinzhou, Liaoning Province, Northeast China (41.10°N, 121.10°E, 50–100 m a.s.l.). This region has a typical continental monsoon climate with a windy spring, a warm and humid summer, and a dry and cold winter. Mean annual air temperature is 8.0 °C, ranging from −27.6 °C in January to 35.0 °C in July. The frost-free period fluctuates around 170–180 days, with an early frost in October and late frost in April. Annual precipitation ranges from 500 to 850 mm, of which 80% falls during June–August (Li et al., 2011). The natural vegetation is mixed broadleaf-conifer forest of warm temperate zone. The dominant canopy species include *Pinus tabuliformis*, *Ulmus davidiana* var. *japonica*, *Fraxinus mandschurica*, and *Juglans mandshurica* (Zhu et al., 2006; Yan et al., 2010).

Based on field surveys of typical stands in the study area, we determined that the mean height (H) of dominant tree species ranged from 15.0 m to 20.0 m. The mean crown widths varied dramatically, so crown widths were classified as 1/3H, 1/4H and 1/5H.

2.2. Meteorological data collection

We collected the meteorological data from 2005 to 2011 in the study site of open area. The observation records included the direct solar radiation and photosynthetically active radiation (PAR) recorded in an interval of 30 min using spectral radiation sensors (TBQ-4-1, LI190SB, LI-COR, Inc., Nebraska, USA), the mean, maximum and minimum temperatures using temperature humidity sensor (EE180, Huitong Ins. Co., LTD., Shenzhen, China), and rainfall using rainfall sensor (SL3-1, Shanghai Meteoro. Ins. Co., LTD., Shanghai, China) in each month. We also obtained the meteorological data from Open Access resources online, for example, monthly sunshine duration in an interval of 30 min (http://cdc.cma.gov.cn/home.do).

2.3. Determining the lower and upper limits of gap size

Many studies have demonstrated that gap light regime drives the other gap microclimate variables such as temperature, soil water content, and snowmelt, which, in turn, exert major influences on the composition and growth of seedlings or saplings within the gap (Zhu et al., 2014). Given the same latitude and topography (slope, aspect, elevation), the amount of solar radiation that can penetrate to the gap is determined by the height of CTSG, and the impact distance of CTSG is correlated to the shadow length of CTSG (Fig. A1). Our approach to define the lower and upper limits of gap size was based on the shadow length cast by CTSG during the growing season. We hypothesize: (i) the minimum shadow length and the maximum-effective shadow length of CTSG represent the shortest distance and the longest distance that CTSG can impact the microclimates in the gap, and (ii) the lower and upper limits of gap size can be objectively defined by the minimum shadow length of CTSG and the maximum-effective shadow length of CTSG, respectively.

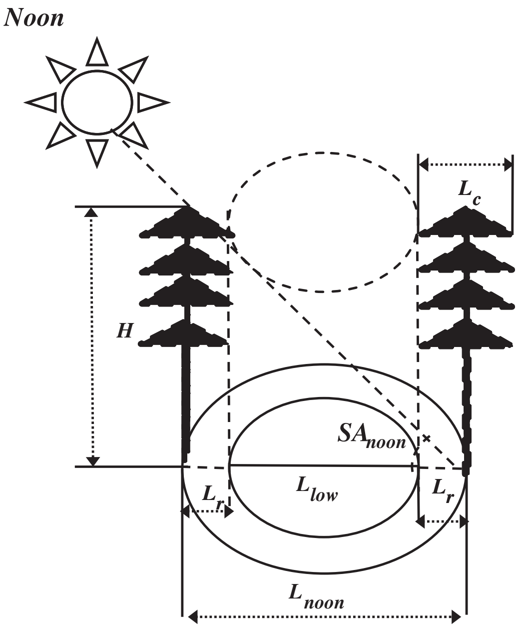


Fig. 1. Sketch for determining the lower limit of gap size. SA_{noon} is solar elevation angle (°) at 12:00 noon (local time); L_r is the shadow length of crown radius (m); L_c is the shadow length of crown width (m), is equal to $2 \times L_r$; H is the mean height of canopy trees surrounding a gap (m); L_{noon} is the shadow length of canopy trees surrounding gap (CTSG) at 12:00 noon (m), which is defined as the lower limit of gap size (m) for expanded gap; L_{low} is the lower limit of gap size (m) for canopy gap, $L_{low} = L_{noon} - 2L_r = L_{noon} - L_c$. Assumption: (i) slope of gap location is 0 degree (on flat land); (ii) H, height of canopy trees surrounding gap is the same.

The lower limit: we determined the minimum gap size based on the shortest shadow length of CTSG and crown width. The crown width could be easily measured in the field (Fig. 1). The shortest shadow length of CTSG is calculated at 12:00 noon (local time) of each day using Eq. (1):

$$L_{noon} = \frac{H}{\tan SA_{noon}} \tag{1}$$

where L_{noon} is the shadow length of CTSG at 12:00, i.e., the gap diameter of the lower limit of gap size (m) for expanded gaps; H is the mean height of the canopy trees (m); SA_{noon} is solar elevation angle (°) at 12:00, which is determined by Eq. (2):

$$SA_{noon} = 90 - (\varphi - \delta) \tag{2}$$

where ϕ is latitude; δ is solar declination angle.

The value of the shortest shadow length of CTSG calculated each day was averaged over the entire growing season, which represents the gap diameter of the lower limit of gap size for expanded gaps. The difference between the mean value of the shortest shadow length of CTSG and the crown width (Eq. (3)) is defined as the gap diameter of the lower limit of gap size (m) for canopy gaps.

$$L_{low} = L_{noon} - L_c \tag{3}$$

where L_{low} is the gap diameter of the lower limit of gap size (m) for canopy gaps; L_c is projected crown width (m).

The upper limit: we assumed that light conditions drive tree regeneration in forest gaps, and that light levels at the center of a large gap should facilitate the regeneration of shade intolerant tree species. We used the photosynthetically active radiation (PAR) of 25000 Lux (450 μmol m^{-2} s^{-1}) as the light compensation point of shade intolerant tree species as suggested by Larcher (1983) and by Deng and Liu (1992) (Fig. A2). Therefore, we used the first and the last time when PAR reached the light saturation point to calculate the maximum-effective shadow length of CTSG each day during the growing season. We recorded PAR once every 30 min on each day during the growing season at the study site. Based on the recorded PAR data, we first determined the initial time (t_s) and the final time (t_e) when the 30-min PAR value reached or exceeded 450 μmol m^{-2} s^{-1} on each day. We then calculated the corresponding tree shadow lengths at t_s and t_e of each day within the growing season using Eqs. (4) and (5) (Fig. 2). Finally, we calculated the maximum-effective shadow length of CTSG on each day using Eq. (6).

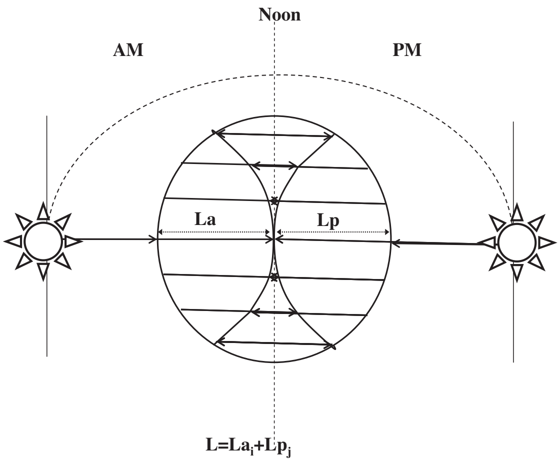


Fig. 2. Sketch for determining the upper limit of gap size. L_a is the shadow length at the initial time (t_s in the morning) when the 30-min PAR is equal to or greater than 450 μmol m^{-2} s^{-1} in the morning; L_p is the shadow length at the final time (t_e in the afternoon) when the 30-min PAR is greater than or equal to 450 μmol m^{-2} s^{-1} in the afternoon. $L_a + L_p$ is defined as the upper limit of gap size for expand gap. If $t_s = t_e$, then $L_a = L_p = L_{noon}$.

$$L_i = \frac{H}{\tan SA_i} \tag{4}$$

where L_i is the shadow length of CTSG at t_s and t_e (m); SA_i is solar elevation angle at any moment (°); H is the mean value of canopy tree height (m).

The solar elevation angle (SA_i) can be obtained from Eq. (5).

$$\sin SA = \sin\varphi \sin\delta + \sin\varphi \cos\delta \cos t \tag{5}$$

where, ϕ is latitude; δ is solar declination angle; t is hour angle.

$$L = L_a + L_p \tag{6}$$

where L_a is the shadow length of CTSG at t_s in the morning (m); L_p is the shadow length of CTSG at t_e in the afternoon (m) (Fig. 2); L is the maximum-effective shadow length of CTSG.

We defined the mean value of L over the growing season as the upper limit of gap diameter (m) for expanded gaps, and the difference between L and L_c (Eq. (7)) as the upper limit of gap diameter for canopy gaps.

$$L_{up} = L - L_c \tag{7}$$

where, L_{up} is the gap diameter of the upper limit of gap size (m) for canopy gaps; L and L_c are previously defined.

3. Results

3.1. The lower limit of gap size

The mean values of the shortest shadow lengths of CTSG at 12:00 averaged 7.6 m (4.8–15.8 m) and 10.2 m (6.4–21.1 m) over the growing season for 15.0 m height stands and 20.0 m height stands, respectively (Fig. 3). The value represents the smallest diameter of the expanded gap because it is the distance of the least impact of CTSG. In order to eliminate the effect of tree heights on gap size, we

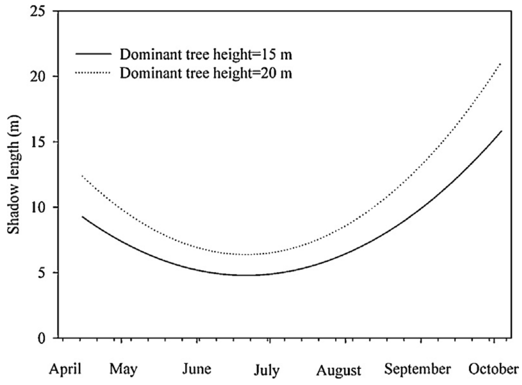


Fig. 3. The shadow length of CTSG at 12:00 noon (local time) on each day of the growing season (during April 15th and October 4th). The height of dominant tree species (H) is 15.0 m or 20.0 m.

calculated the ratio of gap diameter to the height of CTSG ($R_{D/H}$) to determine the lower limit of gap size ($LR_{D/H}$). The mean $LR_{D/H}$ value was calculated as 0.51, which represents the lower limit of gap size for expanded gaps. Depending on the crown width, the lower limits of gap size for canopy gaps was calculated as 0.18, 0.25, and 0.30 for crown width of 1/3H, 1/4H, and 1/5H, respectively. When expressed as gap areas, the lower limits for canopy gaps in the study site ranged from 5.7 m^2 to 15.9 m^2 for the 15.0 m height CTSG, and from 10.2 m^2 to 28.3 m^2 for the 20.0 m height CTSG respectively with crown width from 1/3H, 1/4H, and 1/5H.

3.2. The upper limit of gap size

The mean values of the maximum effective shadow lengths of CTSG in the growing season (averaged from 7-year data) were 49.9 m (45.4–52.9 m) and 66.5 m (60.5–70.5 m) for 15.0 and 20.0 m height stands, respectively (Fig. 4A and B). The mean value of the ratio of gap diameter to dominant tree height ($UR_{D/H}$) is 3.32 (SD = 0.19, $n = 7$) (Fig. 4C), representing the upper limits of gap size for expanded gaps. Therefore, the upper limits of gap size for canopy gaps are 2.99, 3.07 and 3.12 depending on the crown width for 1/3H, 1/4H and 1/5H, respectively (Fig. 4C). When expressed as mean gap area, the upper limit for canopy gaps were 1580.8 m^2, 1670.2 m^2 and 1724.9 m^2 for the 15.0 m height of CTSG, and 2810.4 m^2, 2969.2 m^2 and 3066.5 m^2 for the 20.0 m height of CTSG with crown width for 1/3H, 1/4H and 1/5H, respectively.

4. Discussion

4.1. Method for determining the lower and upper limits of gap size

Most gap studies assume that gaps and non-gaps are discrete and can be easily identified (Runkle, 1992). However, this assumption may not hold true because some forest types may have a more generally open canopy due to widely spaced distribution of trees. Regardless of forest conditions, canopy gaps are directly influenced by the height and crown width of CTSG. We, therefore, proposed using the shadow length of CTSG during the growing season to define the limits of gap size in temperate forests.

The shadow length of CTSG controls light regime within the gap, but it varies greatly with the time of day. We believe that a small canopy opening should not be qualified as a gap if the opening remains shaded even under the shortest shadow length of CTSG, which is calculated at 12:00 on each day of the growing season. The mean shortest shadow length of CTSG over the entire growing season was therefore used as the lower limit of gap size. With increasing gap size, forest gaps would be subjected to decreasing influence of the shadow of CTSG. However, we believe that even a large gap should remain under partial influence from the shadow of CTSG, to differentiate forest gaps from open areas. For the upper limit of gap size, the initial and the final times when the 30-min PAR is greater or equal to 450 μmol m^{-2} s^{-1} in the morning and in the afternoon on each day of the growing season were determined. The maximum-effective projected length can be obtained by Eq. (6) as the upper limit of gap size for expanded gaps.

Because we used only the days in the growing season, i.e., the growing season length, GSL (Linderholm, 2006; Dong et al., 2012), to define the influence of CTSG on the light regime in the gap, temporal and spatial variations in GSL may affect the outcome of the lower and upper limits of gap size. GSL may differ from year to year by up to 20–30 days in temperate forest areas (Li et al., 2011). In our study area, the ratio of shadow length to the height of CTSG did not differ among the three tested GSL: April 15th–October 4th GSL (the long-term mean, 173 days), April 1st–October 18th GSL (201 days), and April 1st–October 31st GSL (214 days) ($p > 0.05$). Therefore, we concluded that the lower and upper limits of gap size were not significantly affected by variations in GSL.

The latitude and solar declination angle of a location influence the lower limit of gap size because they are used to calculate the shadow length at 12:00 noon (Eq. (1)). We tested the effects of latitude (from 35°N to 52°N) on the shadow length at 12:00, and found that the ratio of shadow length of CTSG to tree height at 12:00 increased exponentially by a factor of 0.0414 ($L_{\text{noon}} = a \times e^{0.0414\text{Lt}}$; $R^2 = 0.999$; a is constant depending on tree height; Lt is latitude) with increasing latitude. Therefore, the lower limit of gap size for expanded gaps is constant for a given forest site, but has a higher value in higher latitudes. For example, the ratio of lower limits of gap size for expanded gaps at latitudes of 36.70°N, 39.93°N and 41.10°N with the same GSL (180 days) are 0.46, 0.48 and 0.51, respectively.

Crown width (L_c) is flexible and varies greatly with tree species, which creates uncertainty in determining the lower limit for canopy gaps. In our study area, we determined the lower limits of gap size with crown width varied from 1/3H to 1/5H, which is based on measurements of mature, dominant trees. The lower limit of gap size for canopy gaps varied from $LR_{D/H} = 0.18$ (crown width: 1/3H) to $LR_{D/H} = 0.30$ (crown width: 1/5H) (Table 1). The lower limit of gap size, although constant for expanded gaps, varies with crown width for canopy gaps.

For the same $\text{LR}_{\text{D/H}}$, the canopy gap areas, considering the shape of gaps as a circle for simplicity, are strongly affected by the height of CTSG. For example, if $\text{LR}_{\text{D/H}}$ is 0.25, then the canopy gap areas are 4.9 m^2, 11.0 m^2, 19.6 m^2 and 44.2 m^2 for stands with tree height of 10 m, 15 m, 20 m and 30 m, respectively. Therefore, the lower limit of canopy gap size at a given site, expressed either as gap diameter or ratio of gap diameter to the height of CTSG, is not a fixed value because it varies with both crown width and the height of CTSG.

For the upper limit of gap size, in addition to the influence of latitude and solar declination angle and the height and crown width of CTSG, variations in climatic factors also create uncertainty when calculating the maximum effective shadow length. The initial time and the final time when the 30-min PAR is more than or equal to 450 μmol m^{-2} s^{-1} on each day during the growing season are the key parameters in estimating the maximum effective shadow length, and these change with weather conditions. On cloudy or rainy days when the 30 min PAR never reached 450 μmol m^{-2} s^{-1}, i.e., the initial time and the final time could not be defined, the shadow length was considered to be zero ($L = 0$ in Eq. (6)). When it was cloudy or rainy in the morning and sunny in the afternoon, then, $L = L_p$ because the 30-min PAR never reached 450 μmol m^{-2} s^{-1} before 12:00 ($L_a = 0$); similarly, when sunny in the morning but cloudy or rainy in the afternoon, $L = L_a$. We dou-

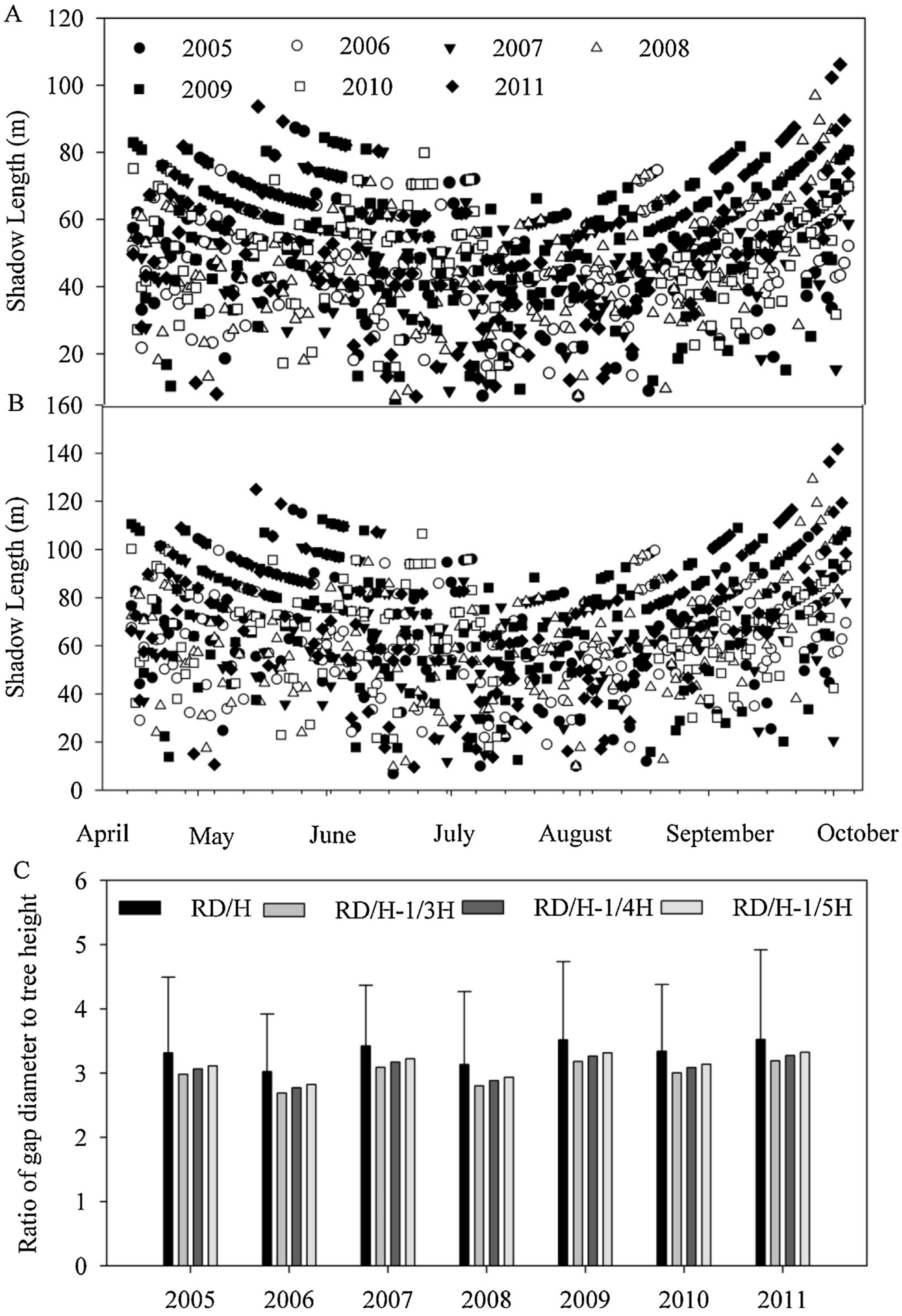


Fig. 4. The shadow length of CTSG when the 30 min PAR is greater than or equal to 450 μmol m^{-2} s^{-1} on each day of the growing season, dominant tree height = 15.0 m (A), dominant tree height = 20.0 m (B). The mean values of ratio of the maximum shadow length to dominant tree height for the growing season (from April 15th to October 4th) during 2005 to 2011 for the crown widths of 1/3H, 1/4H and 1/5H (C).

bled the shadow length on the days with $L = L_{noon}$, $L = L_a$, and $L = L_p$ when the 30-min PAR reach 450 μmol m^{-2} s^{-1} only once during a day. The days when $L = 0$ were excluded. We then calculated the mean maximum effective shadow length (L) during the growing season. As a result, the upper limit of gap size for expanded gaps (L) fluctuates somewhat over years. For example, L was calculated as 66.5 ± 3.8 m for stands with CTSG of 20.0 m tall during seven years between 2005 and 2011.

Similar to the lower limit of gap size, crown width also affects the upper limits of gap size for canopy gaps. This effect, however, is much less because the value of the upper limit is much larger than the value of crown width. Therefore, the upper limit of gap size,

Table 1

Gap limits in Dwa[a] regions. $R_{D/H}$ is the ratio of gap diameter to dominant tree height. Sunshine hours were collected from Meteorological Data Sharing Service System (Available at MDSS: http://cdc.cma.gov.cn/dataSetDetailed.do?changeFlag=detai. Last accessed 8 October 2014).

Location	Geographic coordinate	Sunshine hour (hour)	Expanded gap		$UR_{D/H}$, upper limit of gap size with different crown width				$LR_{D/H}$, lower limit of gap size with different crown width			
			$LR_{D/H}$	$UR_{D/H}$	1/3H	1/4H	1/5H	Mean	1/3H	1/4H	1/5H	Mean
Jinan	36.70°N, 117.00°E Altitude: 58 m	7.56	0.46	3.48	3.15	3.23	3.28	3.22	0.12	0.21	0.26	0.20
Taiyuan	37.78°N, 112.55°EAltitude: 779m	7.60	0.48	3.49	3.15	3.24	3.29	3.23	0.14	0.23	0.28	0.22
Shijiazhuang	38.03°N, 114.42°E Altitude: 81 m	7.33	0.45	3.43	3.10	3.18	3.23	3.17	0.12	0.20	0.25	0.19
Beijing	39.93°N, 116.28°E Altitude: 32 m	7.78	0.48	3.52	3.19	3.27	3.32	3.26	0.15	0.23	0.28	0.22
Jinzhou(study area)	41.10°N, 121.10°E Altitude: 66 m	7.63	0.51	3.49	3.16	3.24	3.29	3.23	0.17	0.26	0.31	0.25
Shenyang	41.73°N, 123.45°E Altitude: 42 m	7.67	0.47	3.50	3.17	3.25	3.30	3.24	0.14	0.22	0.27	0.21
Changchun	43.90°N, 125.22°EAltitude: 237 m	7.72	0.51	3.51	3.18	3.26	3.31	3.25	0.18	0.26	0.31	0.25
Harbin	45.75°N, 126.77°EAltitude: 143 m	7.68	0.54	3.50	3.17	3.25	3.30	3.24	0.21	0.29	0.34	0.28
Mean		7.62	0.49	3.49	3.16	3.24	3.29	3.23	0.15	0.24	0.29	0.23

[a] Dwa: the regions with humid continental hot summer, with severe, dry winter according to Köppen Climate Classification System (Kottek et al., 2006).

when expressed as the ratio of gap diameter to height of CTSG is relatively constant for both canopy and expanded gaps.

4.2. Application of the developed method to temperate forests

Our method was developed based on the meteorological observations in a temperate forest. Consequently, the method may be only applicable to temperate forests where the climatic conditions are similar to the study area (121°10′E, 41°10′N). According to the Köppen Climate Classification System (Kottek et al., 2006), our study area is located in Dwa regions, which covers most of Northeast China, North China, south part of Northwest China, most of the Korean Peninsula, south part of Russian Far East (Fig. A3). Therefore, we applied the method to estimate the limits of gap size for several locations in Dwa regions: Jinan (36.70°N, 117.00°E, altitude 58 m), Beijing (39.93°N, 116.28°E, altitude 32 m), Jinzhou (the study area), Shenyang (41.73°N, 123.45°E, altitude 42 m), Changchun (43.90°N, 125.22°E, altitude 237 m) and Harbin (45.75°N, 126.77°E, altitude 143 m) in China.

We estimated the lower limits of gap size in Dwa regions by calculating the minimum shadow length of CTSG for expanded gaps, with considering different crown width 1/3H, 1/4H and 1/5H for canopy gaps (Table 1). The lower limits of gap size in the form of $R_{D/H}$ generally are constant for both expanded and canopy gaps with the same crown width (Table 1), but it varied between 0.12 and 0.34 with a mean of 0.23 in the Dwa regions we tested for canopy gaps. This range is above the smallest value (0.05) found in the literature worldwide, but includes about 56% of observations in the literature (Table A1).

In order to estimate the upper limits of gap size in Dwa regions, we obtained meteorological data, including GSL and the mean sunshine duration (SD) each day for the growing season, from the Chinese Meteorological Data Sharing Service System (MDSS). We used the Chinese international exchange station ground climate values calculated for 30 years (1971–2000) with the code "SURF_CLI_CHN_ MUL_MMON_19712000_CES" (Table 1). As the initial and final time of each day when the 30-min PAR is greater than or equal to 450 μmol m^{-2} s^{-1} within the growing season cannot be obtained from the MDSS data set, we developed a regression model to predict $R_{D/H}$ from SD data during the growing season for 2005–2011 in our study area (Fig. 5, Eq. (8)).

$$R_{D/H} = 0.2041 \times \mathrm{SD} + 1.9362 (R^2 = 0.8632) \tag{8}$$

where, $R_{D/H}$ is the mean ratio of the maximum effective shadow length to the height of CTSG; SD is mean sunshine duration during the growing season (hours per day).

The mean values applied in Eq. (8) were obtained from the meteorological data observed during 2005–2011. However, the mean daily value of sunshine duration within the seven years (7.635 h) is almost identical to the mean value from long-term observation (7.634 h from 1970 to 2011), suggesting the mean sunshine hours during the growing season is relatively stable for our study area. Using Eq. (8), the estimated $R_{D/H}$ averaged 3.23 (canopy gap), with a range from 3.10 to 3.32 for the selected Dwa regions (Table 1). Approximately 80% of the gap upper limits in the form of $R_{D/H}$ reported in the literature fell within 3.23, and about 20% were over 3.23 (Table A1). The mean $R_{D/H}$ reported in the literature for Dwa regions was 2.36, varying from 0.63 to 7.56 (Table A1). This wide range of upper limits reported in the existing literature reflects the lack of an objective method to define gap size.

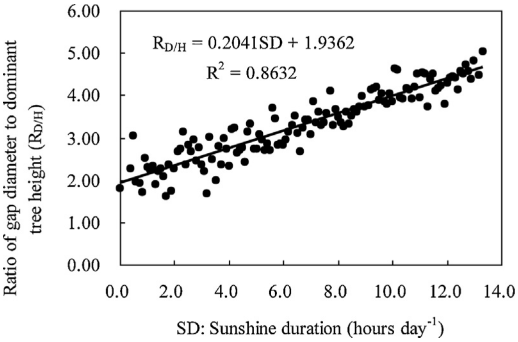


Fig. 5. The relationship between the ratio of the maximum effective shadow length to dominant tree height and the sunshine duration (hours day^{-1}). Note: the ratio and sunshine hour were obtained by averaging the data observed on each day of the growing season (from April 15th to October 4th) during 2005–2011.

4.3. Modification of the developed method for the application to forests worldwide

The lower limit of gap size is determined only by the location and the height of CTSG, which should be applicable worldwide. However, the determination of the upper limit of gap size using this method depends on the long-term observation of PAR, which may not be readily available. Consequently, we propose a modified method for determining the upper limit of gap size using the sunshine duration, a more easily obtained variable from meteorological stations worldwide.

In theory, the sunshine duration (the length of time when direct solar irradiance exceeds 120 W m^{-2} in a day) and the PAR duration (the length of time when direct solar irradiance exceeds 179.8 W m^{-2}, or PAR is 450 μmol m^{-2} s^{-1}) can be calculated by determining the initial and final times when the direct solar irradiance exceeds 120 W m^{-2} or 179.8 W m^{-2} on any day. However, theoretical values are quite different from the actual observations

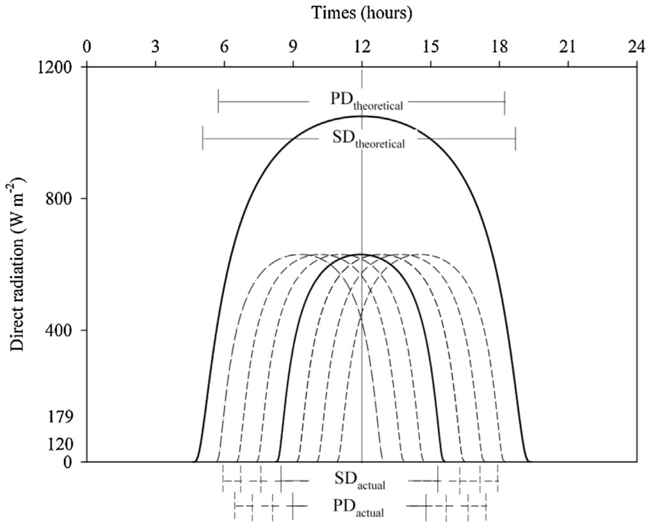


Fig. 6. An illustration for determining the thresholds of effective sunshine time or light saturation point time in theory. SD$_{\text{theoretical}}$ is theoretical sunshine duration (hour), SD$_{\text{actual}}$ is actual sunshine duration (hour), PD$_{\text{theoretical}}$ is theoretical photosynthetic active radiation (PAR) duration (hour), and PD$_{\text{actual}}$ is actual PAR duration (hour).

because many factors influence direct solar irradiance. In order to obtain the actual PAR duration (PD$_{\text{actual}}$) without observation, we employed a coefficient γ (Eq. (9)), which represents the synthesis of local climate factors influencing the solar irradiance. Therefore, the actual PAR duration can be obtained by γ (Eq. (10)) and the theoretical PAR duration (PD$_{\text{theoretical}}$) because the coefficient γ is a constant for a long-term observation in a given forest site (WMO, 2008).

$$\gamma = \text{SD}_{\text{actual}}/\text{SD}_{\text{theoretical}} \tag{9}$$

$$\text{PD}_{\text{actual}} = \gamma \text{PD}_{\text{theoretical}} \tag{10}$$

where γ is the synthesis of local climate factors influencing the solar irradiance; SD$_{\text{actual}}$: actual sunshine duration, SD$_{\text{theoretical}}$: theoretical sunshine duration; PD$_{\text{actual}}$ is actual PAR duration, PD$_{\text{theoretical}}$ is theoretical PAR duration.

The estimated PD$_{\text{actual}}$ only indicates the period when PAR exceeds 450 μmol m^{-2} s^{-1} on a day, but it can not tell the initial and final times, which change greatly as shown in Fig. 6. Theoretically, the solar irradiance has a symmetrical distribution with the peak value at 12:00 noon (local solar time) (Fig. 6), which may hold true with actual long-term observations. Therefore, the initial time (t_s) and the final time (t_e) could be obtained by dividing PD$_{\text{actual}}$ into bisections around 12:00 noon (Fig. 6). The upper limit of gap size could then be determined by calculating the shadow length of CTSG at t_s and t_e. When applied in our study area, the upper limit for canopy gap in form R$_{\text{D/H}}$ was 3.21, which is very close to the estimation 3.23 based on actual PAR observations. This result suggests that it may be possible to determine the upper limit of gap size without using actual PAR observations. However, future tests on other forest sites with the observed PAR data are needed.

5. Conclusions

We developed an approach to determine the gap size thresholds by considering the effects of CTSG on the light environment within the gap. The ratio of gap diameter to the height of CTSG was proposed to classify the gap sizes.

The mean shadow length of CTSG at 12:00 noon on each day during the growing season represents the least impact of CTSG on the gap environment, which is used to define the lower limit of gap size. The lower limit of gap size averaged 0.49 for expanded gaps (0.45–0.54) and 0.23 (0.12–0.34) for canopy gaps depending on crown width for Dwa regions.

The upper limit of gap size was defined by the maximum effective shadow length of CTSG calculated at the initial and the final times when the 30-min PAR is more than or equal to the light saturation point for shade intolerant tree species. This definition is based on considering the effect of the farthest impact of CTSG on the growth of shade intolerant tree species. The upper limit of gap size averaged 3.49 for expanded gaps (3.43–3.52) and 3.23 (3.10–3.32) for canopy gaps depending on crown width for Dwa regions. Since the upper limit of gap size is affected by local climate and thus varies with locations, we developed an empirical model that predicts R$_{\text{D/H}}$ from SD in order to apply the approach in temperate forests similar to the study area. We also proposed another modified method that could potentially be applied to forests worldwide.

Considering various gap sizes presented in literature, we propose a simple classification of forest gaps in temperate forests: small gap, $R_{\text{D/H}} \le 1.0$; medium gap, $1.0 < R_{\text{D/H}} \le 2.0$; and large gap, $R_{\text{D/H}} > 2.0$. We suggest that our methods, including the modified method for determining the upper limit without using actual PAR observation, should be tested to determine the gap thresholds in other forests so that the gap limits can be objectively determined and consistently used in future studies worldwide.

Acknowledgements

We thank Dr. Tian GAO, Mr. Yirong SUN and Mr. Guiduo SHANG for their helpful suggestions in this study. This study was financially supported by National Natural Science Foundation of China (31330016), and the National Basic Research Program of China (2012CB416906). We have no conflict of interest.

Appendix A

See Figs. A1–A3 and Table A1 .

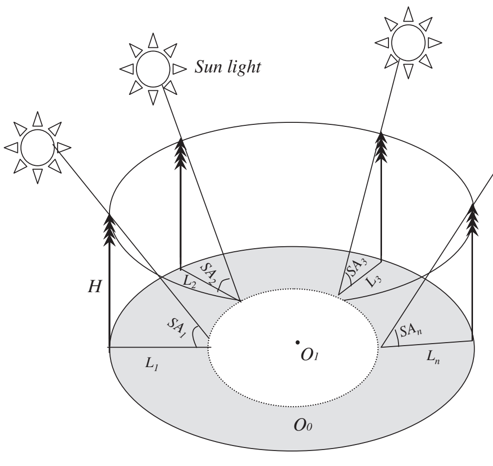


Fig. A1. An illustration of the impact range of canopy trees surrounding a gap (CTSG). H is the height of canopy trees surrounding the gap (m); $L_1, L_2, L_3, \ldots, L_n$ are the maximum shadow length of CTSG at any moment; SA$_1$, SA$_2$, SA$_3$, ..., SA$_n$ are solar elevation angle at any moment; O_1 (the dashed-line circle) represents the area beyond the shadow length; O_0 (the area between the solid-line circle and the dashed-line circle) represents the area within the range of the shadow length, which is the upper limit of gap size. Assumptions: (i) the slope is 0 degree (on flat land); (ii) the height of canopy trees surrounding the gap is the same.

Table A1

Gap sizes reported in published studies from 1996 to 2013. Listed in order of their publication date. Only studies that clearly indicated the height of dominant tree species were selected. The lower limit of gap size is the minimum gap size reported in each study. The upper limit of gap size is the maximum gap size reported in a study. Mean gap diameter (m) was determined from the gap area by assuming the gap to be circular, or vice versa. Mean 1, Min 1, and Max 1 are the mean, minimum, and maximum from all the selected studies. Mean 2, Min 2, and Max 2 are the mean, minimum, and maximum from the selected studies between 35.00°N and 55.00°N.

Published time	Author(s)	Journal, volume and page	Location (N, E)	Forest cover type	Forest age (year)	Height of dominant tree species (H) (m)	Lower limit of gap size		Upper limit of gap size	
							Area (m^2)	Ratio of gap diameter to H	Area (m^2)	Ratio of gap diameter to H
1997	Gray, A.N. and Spies, T.A.	J. Ecol., 84, 635–645.	44°15′∼45°50′N, 121°49′∼122°15′W	*Pseudotsuga menziesii*	Old∼growth/ 90∼500	42.5	40.0	0.168	2000.0	1.187
1997	Rao, P., Barik, S.K., Pandey, H.N. and Tripathi, R.S.	Aust. J. Ecol., 22, 136–145.	25°34′N, 91“56′E	Subtropical forest/*Quercus* and *Schima khasia*		21.0	20.0	0.240	950.0	1.656
1998	van der Meer, P.J. and Dignan, P.	Forest Ecol. Manag., 244, 102–111.	37°48′S, 146°12′E	*Eucalyptus regnans*		50.0	100.0	0.226	19600.0	3.159
1999	Yamamoto, S. and Nishimura, N.	Plant Ecol., 140, 167–176.	35°21′77″N, 133°33′23″E	*Fagus crenata*	Secondary developing/ Primary old∼growth	17.5/22.5	20.0	0.288/0.224	585.1	1.560/1.213
1999	Drobyshev, I.V.	Forest Ecol. Manag., 115, 71–83.	56°26′∼56°31′N, 32°29′∼33°01′E	Spruce forest		21.0	40.0	0.340	17000.0	7.006
2000	Tabarelli, M. and Mantovani, W.	Plant Ecol., 148, 149–155.	23°17′S, 45°30′W	Tropical montane rain forest		20.0	30.3	0.311	500.5	1.262
2002	Coates, K.D.	Forest Ecol. Manag., 155, 387–398.	55°22′N, 127°50′W	*Tsuga heterophylla*		30.0	20.0	0.168	5000.0	2.660
2002	Grau, H.R.	Ecology, 83, 2591–2601.	27°30′S, 65°40′W	Subtropical montane forest	>65	17.5	25.0	0.322	2640.0	3.313
2002	Martins, S.V. and Rodrigues, R.R.	Plant Ecol., 163, 51–62.	22°49′45″S, 47°06′33″W	Semideciduous mesophytic forest		20.0	20.1	0.253	468.0	1.221
2003	Hoshino, D., Nishimura, N. and Yamamoto, S.	Forest Ecol. Manag., 175, 141–152.	35°43′57″N, 137°37′50″E	*Thujopsis dolabrata*		27.5	25.0	0.205	300.0	0.711
2003	McAlpine, K.G. and Drake, D.R.	Plant Ecol., 165, 207–215.	41°18.3′S, 174°44.8′E	*Pinus radiata*	50∼55	40.0	251.2	0.447	1122.6	0.945
2003	Zhu, J.J., Matsuzaki, T., Lee, F.Q. and Gonda, Y.	Forest Ecol. Manag., 182, 339–354.	37°52′41.3″N, 138°56′16.8″E	Coastal pine forest	40	6.7	8.8	0.500	86.5	1.567
2004	Clarke, P.J.	J. Ecol., 92, 203–213.	19°17′S, 147°03′E	Mangrove forests/Rhizophora		7.0	50.0	1.140	225.0	2.418
2004	Obiri, J.A.F. and Lawes, M.J.	J. Veg. Sci., 15, 539–547.	31°37′S, 29°31′E	Evergreen forest		19.7	15.7	0.227	395.6	1.139
2004	York, R.A., Heald, R.C., Battles, J.J. and York, J.D.	Can. J. Forest Res., 34, 630–641.	38°52′N, 120°40′W	mixed∼conifer forest	50∼60	30.5	1000.0	1.170	10000.0	3.700
2005	Diaci, J., Pisek, R. and Boncina, A.	Eur. J. Forest Res., 124, 29–36.	46°35′N, 13°58′E	Subalpine Norway spruce forest		35.0	100.0	0.322	800.0	0.912

Table A1 (*Continued*).

Published time	Author(s)	Journal, volume and page	Location (N, E)	Forest cover type	Forest age (year)	Height of dominant tree species (H) (m)	Lower limit of gap size		Upper limit of gap size	
							Area (m^2)	Ratio of gap diameter to H	Area (m^2)	Ratio of gap diameter to H
2005	Grogan, J., Landis, R.M., Ashton, M.S. and Galvao, J.	Forest Ecol. Manag., 204, 399–412.	6.5–8°S, 49.5–52°W	Mahogany		28.0	241.0	0.626	1106.0	1.340
2006	Galhidy, L., Mihok, B., Hagyo, A., Rajkai, K. and Standovar, T.	Plant Ecol., 183, 133–145.	47.9°N, 18.9°E	*Fagus sylvatica*		25.0	78.5	0.400	1256.0	1.600
2006	Huth, F. and Wagner, S.	Forest Ecol. Manag., 229, 314–324.	50°00′N, 13°35′E	*Picea abies* stands	90~121	26.5	21.0	0.195	2157.0	1.978
2006	Mountford, E.P., Savill, P.S. and Bebber, D.P.	Forestry, 79, 389–408.	51.5°N, 1.0°W	Semi~natural and replanted stands/beech		27.5	75.0	0.355	241.0	0.637
2006	Shure, D.J., Phillips, D.L. and Bostick, P.E.	Plant Ecol., 185, 299–318.	35°02′N, 83°11′W	Hardwood forest	70	21.1	160.0	0.676	20000.0	7.563
2006	Wang, W., Franklin, S.B., Ren, Y. and Ouellette, J.R.	Forest Ecol. Manag., 234, 107–115.	33°33′~33°46′N, 107°40′~107°55′E	*Fargesia dracocephala*		3.6	23.8	1.529	594.2	7.640
2007	Arevalo, J.R. and Fernandez-Palacios, J.M.	Plant Ecol., 188, 133–143.	28°19′N, 16°34′W	Laurel forest		15.0	125.0	0.841	268.0	1.231
2007	Martini, A.M.Z. and dos Santos, F.A.M.	Plant Ecol., 190, 81–95.	15°10′S, 39°03′W	Tropical moist forest		27.5	65.4	0.332	260.9	0.663
2007	van der Meer, P.J. and Dignan, P.	Forest Ecol. Manag., 244, 102–111.	37°48′S, 146°12′E	*Eucalyptus regnans*		52.5	100.0	0.215	20000.0	3.040
2008	de Lima, R.A.F. and de Moura, L.C.	Plant Ecol., 197, 239–253.	24°20′S, 47°44′W	Old~growth forest		22.5/27.5	7.8/15.2	0.140/0.160	266.3/276.5	0.818/
2008	Gutierrez, A.G., Aravena, J.C., Carrasco-Farias, N.V., Christie, D.A., Fuentes, M. and Armesto, J.J.	J. Biogeogr., 35, 1674–1687.	41.6°S, 73.9°W	Temperate coastal rain forest	>286	25.0	31.0	0.251	292.1	0.771/0.682
2008	Kenderes, K., Mihok, B. and Standovar, T.	Forestry, 81, 111–123.	48°03 ′N, 20°27′E	Beech forest/*Fagus sylvatica*	150~200	44.0	4.0	0.051	870.0	0.756
2008	Malizia, A. and Grau, H.R.	J. Veg. Sci., 19, 597–604.	26°76′S, 65°33′W	Neotropical Andean montane forests		22.5	11.0	0.166	130.0	0.572

Table A1 (*Continued*).

Published time	Author(s)	Journal, volume and page	Location (N, E)	Forest cover type	Forest age (year)	Height of dominant tree species (H) (m)	Lower limit of gap size		Upper limit of gap size	
							Area (m^2)	Ratio of gap diameter to H	Area (m^2)	Ratio of gap diameter to H
2008	Schulze, M.	Forest Ecol. Manag., 255, 866–879.	3°43′S, 48°17′W	Tropical moist forest		37.5	165.0	0.387	450.0	0.638
2008	Toledo-Aceves, T. and Swaine, M.D.	J. Veg. Sci., 19, 717–U770.	6°44′∼ 6°40′N, 1°15′∼ 1°22′W	Moist semi∼deciduous forest		35.0	38.8	0.201	196.5	0.452
2010	Abd Latif, Z. and Blackburn, G.A.	Int. J. Biometeorol., 54, 119–129.	54°10′N, 2°49′W	Mixed semi∼natural deciduous forest/*Quercus petraea*, *Fagus sylvatica*, and *Fraxinus excelsior*		25.0	40.0	0.285	286.0	0.763
2010	Gasser, D., Messier, C., Beaudet, M. and Lechowicz, M.J.	Forest Ecol. Manag., 259, 2006–2014.	47°04′N, 72°15′W	Sugar maple, yellow birch, and beech		19.5	100.0	0.579	1000.0	1.830
2010	Kathke, S. and Bruelheide, H.	Forest Ecol. Manag., 259, 1597–1605.	51°48′6″N, 10°37′5″E	Near∼natural Norway spruce forest	200	42.5	131.0	0.304	16400.0	3.400
2010	Muscolo, A., Sidari, M., Bagnato, S., Mallamaci, C. and Mercurio, R.	Eur. J. Forest Res., 129, 355–365.	38°33′N, 16°19′E	Silver∼beech stands/*Abies alba*	90	30.5	185.0	0.503	410.0	0.749
2012	Yan, Q.L., Zhu, J.J. and Yu, L.Z.	Plos One, 7, e39502.	41°51′N, 124°54′E	Mixture of broadleaved native tree species	50	16.5	52.3	0.495	698.4	1.807
2013	Zhang, C., Zou, C.J., Peltola, H., Wang, K.Y. and Xu, W.D.	New Forest, 44, 297–310.	43°30′∼43°36′N, 117°06′∼117°16′E	Semi∼arid forest∼steppe ecotone/*Picea mongolica*		17.0	50.0	0.469	3000.0	3.636

Table A1 (*Continued*).

Published time	Author(s)	Journal, volume and page	Location (N, E)	Forest cover type	Forest age (year)	Height of dominant tree species (H) (m)	Lower limit of gap size		Upper limit of gap size	
							Area (m^2)	Ratio of gap diameter to H	Area (m^2)	Ratio of gap diameter to H
2013	Mallik, A.U., Kreutzweiser, D.P., Spalvieri, C.M. and Mackereth, R.W.	Forest Ecol. Manag., 289, 209–218.	48°21′5″N, 85°20′46″W	Mixedwood forest/*Populus tremuloides*	75	11.7	10.0	0.305	400.0	1.929
2013	Donoso, P.J., Soto, D.P., Coopman, R.E. and Rodriguez-Bertos, S.	Bosque, 34, 23–32.	39°35′S, 72°05′W	Old∼growth forest/red maple, yellow birch, and eastern hemlock		22.5	40.0	0.317	734.0	1.359
2013	Arihafa, A. and Mack, A.L.	Pac. Sci., 67, 47-58.	6°43′S, 145°05′E	Typical lower montane primary forest		40.0	71.0	0.238	530.0	0.649
Mean 1						26.1	86.4	0.401	3192.4	2.016
Min 1						3.6	4.0	0.051	86.5	0.452
Max 1						52.5	1000.0	1.551	20000.0	7.640
Mean 2						24.7	91.3	0.362	3637.3	2.359
Min 2						6.7	4.0	0.051	86.5	0.629
Max 2						44.0	1000.0	1.170	20000.0	7.563

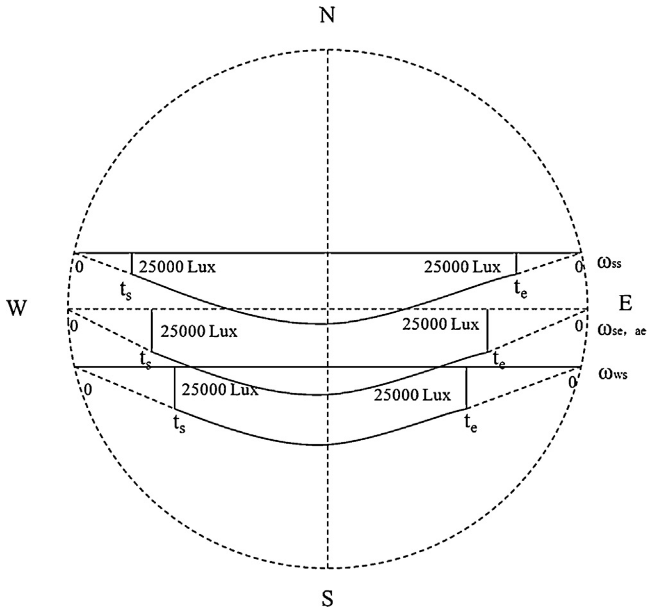


Fig. A2. An illustration for determining the thresholds of effective sunshine time or light saturation point time. ωse and ωae are, respectively, the trajectory of the sun on the vernal equinox and autumnal equinox (the same dashed-line, WE); ωss is the trajectory of the sun on the summer solstice; ω_{ws} is the trajectory of the sun on the winter solstice; 25000 Lux (450 μmol m^{-2} s^{-1}) is the mean PAR (in 30 min) applied to define the light saturation point of shade intolerant tree species as suggested by Larcher (1983) and by Deng and Liu (1992); the initial time (t_s) is defined as the mean PAR (in 30 min) greater than or equal to 25000 Lux (450 μmol m^{-2} s^{-1}); and the final time (t_e) is defined as the mean PAR (in 30 min) equal to or greater than 25000 Lux (450 μmol m^{-2} s^{-1}). The time period is defined as the solid-line curves between the initial time (t_s) and the final time (t_e).

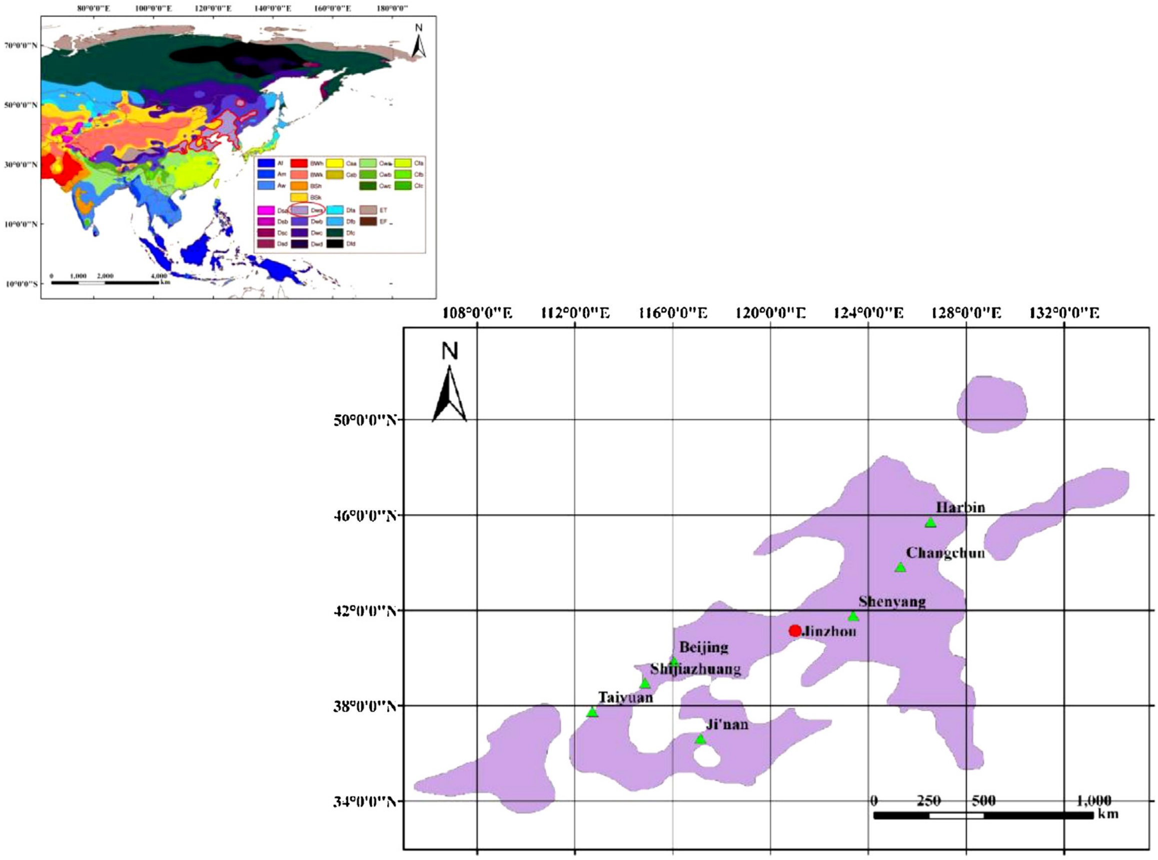


Fig. A3. Map of Dwa regions according to the Köppen–Geiger classification.

(Cited and amended from Kottek et al., 2006)

References

Arevalo, J.R., Fernandez-Palacios, J.M., 2007. Treefall gaps and regeneration composition in the laurel forest of Anaga (Tenerife): a matter of size? Plant Ecol. 188, 133–143.

Brokaw, N.V.L., 1982. The definition of treefall gap and its effect on measures of forest dynamics. Biotropica 14, 158–160.

Clarke, P.J., 2004. Effects of experimental canopy gaps on mangrove recruitment: lack of habitat partitioning may explain stand dominance. J. Ecol. 92, 203–213.

de Grandpre, L., Boucher, D., Bergeron, Y., Gagnon, D., 2011. Effects of small canopy gaps on boreal mixedwood understory vegetation dynamics. Commun. Ecol. 12, 67–77.

de Lima, R.A.F., 2005. Gap size measurement: the proposal of a new field method. For. Ecol. Manage. 214, 413–419.

Deng, S.L., Liu, W.Z., 1992. Geological Dictionary. Hebei Education Press, Shijiazhuang.

Dong, M.Y., Jiang, Y., Zheng, C.T., Zhang, D.Y., 2012. Trends in the thermal growing season throughout the Tibetan Plateau during 1960–2009. Agric. For. Meteorol. 166, 201–206.

Ediriweera, S., Singhakumara, B.M.P., Ashton, M.S., 2008. Variation in canopy structure, light and soil nutrition across elevation of a Sri Lankan tropical rain forest. For. Ecol. Manage. 256, 1339–1349.

Elias, R.B., Dias, E., 2009. Gap dynamics and regeneration strategies in Juniperus-Laurus forests of the Azores Islands. Plant Ecol. 200, 179–189.

Garbarino, M., Mondino, E.B., Lingua, E., Nagel, T.A., Dukic, V., Govedar, Z., Motta, R., 2012. Gap disturbances and regeneration patterns in a Bosnian old-growth forest: a multispectral remote sensing and ground-based approach. Ann. For. Sci. 69, 617–625.

Gray, A.N., Spies, T.A., 1996. Gap size, within-gap position and canopy structure effects on conifer seedling establishment. J. Ecol. 84, 635–645.

Green, P.T., 1996. Canopy gaps in rain forest on Christmas Island, Indian ocean: size distribution and methods of measurement. J. Trop. Ecol. 12, 427–434.

Hu, L., Zhu, J., 2009. Determination of the tridimensional shape of canopy gaps using two hemispherical photographs. Agric. For. Meteorol. 149, 862–872.

Hubbell, S.P., Foster, R.B., O'Brien, S.T., Harms, K.E., Condit, R., Wechsler, B., Wright, S.J., de Lao, S.L., 1999. Light-gap disturbances, recruitment limitation, and tree diversity in a neotropical forest. Science 283, 554–557.

Humber, J.M., Hermanutz, L., 2011. Impacts of non-native plant and animal invaders on gap regeneration in a protected boreal forest. Biol. Invasions 13, 2361–2377.

Kenderes, K., Mihok, B., Standovar, T., 2008. Thirty years of gap dynamics in a central european beech forest reserve. Forestry 81, 111–123.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Koppen–Geiger climate classification updated. Meteorol. Zeitschrift 15, 259–263.

Larcher, W., 1983. Physiological Plant Ecology, 2nd Ed. Springer-Verlag, New York, USA.

Lawton, R.O., Putz, F.E., 1988. Natural disturbance and gap-phase regeneration in a wind-exposed tropical cloud forest. Ecology 69, 764–777.

Li, Z.G., Tan, H.J., Yang, P., Zhou, Q.B., Wang, Y.L., Wu, W.B., Yin, H., Zhang, L., 2011. Identification and application of seasonality parameters of crop growing season in Northeast China based on NDVI Time Series Data. Acta Scientiarum Natura1ium Universitatis Pekinensis 47, 882–892.

Linderholm, H.W., 2006. Growing season changes in the last century. Agric. For. Meteorol. 137, 1–14.

Muscolo, A., Sidari, M., Bagnato, S., Mallamaci, C., Mercurio, R., 2010. Gap size effects on above- and below-ground processes in a silver fir stand. Eur. J. For. Res. 129, 355–365.

Myers, G.P., Newton, A.C., Melgarejo, O., 2000. The influence of canopy gap size on natural regeneration of Brazil nut (*Bertholletia excelsa*) in Bolivia. For. Ecol. Manage. 127, 119–128.

Nakashizuka, T., Katsuki, T., Tanaka, H., 1995. Forest canopy structure analyzed by using aerial photographs. Ecol. Res. 10, 13–18.

Quine, C.P., 2001. A preliminary survey of regeneration of Sitka spruce in wind-formed gaps in British planted forests. For. Ecol. Manage. 151, 37–42.

Runkle, J.R., 1982. Patterns of disturbance in some old-growth mesic forests of eastern North-America. Ecology 63, 1533–1546.

Runkle, J.R., 1992. Guidelines and sample protocol for sampling forest gaps. In: General Technical Report PNW-GTR-283 (ed. USDA Forest Service). Pacific Northwest Research Station, Portland, OR, USA, pp. 48.

Schliemann, S.A., Bockheim, J.G., 2011. Methods for studying treefall gaps: A review. For. Ecol. Manage. 261, 1143–1151.

Sefidi, K., Mohadjer, M.R.M., Mosandl, R., Copenheaver, C.A., 2011. Canopy gaps and regeneration in old-growth Oriental beech (*Fagus orientalis* Lipsky) stands, northern Iran. For. Ecol. Manage. 262, 1094–1099.

Shure, D.J., Phillips, D.L., Bostick, P.E., 2006. Gap size and succession in cutover southern Appalachian forests: An 18 year study of vegetation dynamics. Plant Ecol. 185, 299–318.

ter Steege, H., 1993. HEMIPHOT, a programme to analyze vegetation indices, light and light quality from hemispherical photographs. Wageningen, The Tropenbos Foundation.

Veblen, T.T., 1985. Forest Development in Tree-Fall Gaps in the Temperate Rain Forests of Chile. Natl. Natl. Geogr. Res. 1, 162–183.

Watt, A.S., 1947. Pattern and process in the plant community. J. Ecol. 35, 1–22.

WMO, Guide to Meteorological Instruments and Methods of Observation, 7th Ed. (2008) Available at: http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf.Last

Yan, Q.L., Zhu, J.J., Zhang, J.P., Yu, L.Z., Hu, Z.B., 2010. Spatial distribution pattern of soil seed bank in canopy gaps of various sizes in temperate secondary forests, Northeast China. Plant Soil 329, 469–480.

Zhu, J.J., Hu, L.L., Yan, Q.L., Sun, Y.R., Zhang, J.X., 2009. A new calculation method to estimate forest gap size. Front. For. China 4, 276–282.

Zhu, J.J., Lu, D.L., Zhang, W.D., 2014. Effects of gaps on regeneration of woody plants: a meta-analysis. J. For. Res. 25, 501–510.

Zhu, J.J., Matsuzaki, T., Lee, F.Q., Gonda, Y., 2003. Effect of gap size created by thinning on seedling emergency, survival and establishment in a coastal pine forest. For. Ecol. Manage. 182, 339–354.

Zhu, J.J., Li, X.F., Liu, Z.G., Cao, W., Gonda, Y., Matsuzaki, T., 2006. Factors affecting the snow/wind induced damage of a montane secondary forest in Northeastern China. Silva Fennica 40, 37–51.