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
Available online 6 July 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
0168-1923/

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.