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Spatial distribution and growth association of regeneration in gaps of Chinese pine (*Pinus tabuliformis* Carr.) plantation in northern China

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ABSTRACT

Chinese pine is one of the major afforestation species in North China, and plantations of this species are of great significance for improving the ecological environment and for conserving soil and water. However, most of the Chinese pine plantations established by the government in the 1970s are mature or nearly mature. Therefore, how to successfully promote natural regeneration has become a major issue in plantation management. We established four types of gaps with different diameters in a plantation in northern China based on the average canopy height (H), i.e., L-I (0.75 H), L-II (1.00 H), L-III (1.25 H), and L-IV (1.50 H). Seven years after gap creation, each gap was divided into four aspects by vertical lines along the main direction of the gap center. Additionally, three sections were partitioned in each gap according to the mean crown radius of the border trees; these sections were the central area of the gap (section B), the inner edge of the gap (section C) and the outer edge of the gap (section D). The results showed that there were no differences in density among gap size classes and gap aspects, but a positive response was observed for regeneration growth. The maximum growth in L-III implied that this gap was the optimal size for promoting the establishment, survival and development of regenerated trees. The highest density and greatest growth occurred mostly along the gap edge. Spatial patterns of abundance were generally concurrent with patterns of regeneration stature (e.g., height) in all tested gaps. However, the spatial distributions of regeneration density and growth exhibited obvious differences in different gap size classes, which likely resulted from heterogeneity in the micro-environment within the gap and the differences in the regeneration responses to these variations. The mark correlation function indicated that spatial autocorrelation characteristics of regeneration growth within gaps and gap sections were mainly independent. Collectively, our findings suggested that the expansion of gaps with continuous monitoring will likely be necessary to promote further canopy recruitment. Additionally, regenerating trees exhibited different spatial distributions and could be more resilient to various interferences. Factors influencing the differences in spatial distribution need to be further studied in light of the relationship between variations in the micro-environment and regeneration responses after gap creation. Moreover, whether large-scale vegetation displacement and reorganization will result from clear cutting these plantations warrants further investigation.

1. Introduction

In recent decades, forestry has been undergoing a transition from the domination of wood production to ecological construction and from single-structure forests to forests with multi-level complex structures due to the prevalence of near-natural forest management (Coates and Burton, 1997; Nakamura et al., 2005). The ultimate goal of these transitions is to achieve sustainable forest development. Therefore, we can make full use of the natural regeneration capability of trees to maintain stability and to achieve continuous coverage in plantation management (Zhou and Sheng, 2008). Natural regeneration is the process of self-improvement, self-adaptation, and continuous improvement of quality, and this process plays an important role in the replacement of forests (Lu et al., 2009). Natural regeneration is characterized by various layers of different-aged species, as well as abundant species, strong adaptability, high productivity and genetic quality (Moktan et al., 2009). However, there is a problem to be solved in the sustainable management of plantations that adopted silvicultural measures to promote natural regeneration and then improve forest stability and enrich community structure. The creation of gaps has long

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been considered an effective silvicultural measure to maintain the stability of the plantation structure, ensure the successful regeneration of tree species, and ultimately achieve continuous forest cover (Schütz, 2001; Taki et al., 2010; Hale, 2003). The establishment of gaps in a silvicultural system is based mainly on the removal of one or more canopy trees in a closed forest, which increases the environmental heterogeneity by directly increasing the amount of light in the gaps (Nakamura et al., 2005; Dupuy and Chazdon, 2008). Some previous studies suggested that gap creation not only provided sites for the occurrence and development of regeneration but also created a favorable environment for the growth and coexistence of multiple species (Elias and Dias, 2009; Garbarino et al., 2012). Therefore, the main purpose of this study was to explore the effects of gap size on regeneration in Chinese pine (*Pinus tabulaeformis*) plantations.

Although natural regeneration plays an important role in optimizing forest structure, seed germination, seedling establishment and survival of local dominant tree species in gaps are often influenced by site conditions, light, and other biological and/or abiotic factors (Hooper et al., 2010; Holl et al., 2010). Some studies have shown that these factors also vary in different locations of the same gap, resulting in environmental heterogeneity within the gap (Duguid et al., 2013; He et al., 2015). In particular, the most direct and important role played by gap creation is the effect on the light environment. The light intensity gradually weakens with increasing distance from the center of the gap to the edge of the gap, where the greatest change in light intensity occurs (Liu and Wu, 2002). Ritter et al. (2005) found that photosynthetically active irradiance was highest in the northern part of the gap and in the adjacent forest. In addition, the creation of gaps can also affect the distribution of litter within a gap (Dupuy and Chazdon, 2008) and, in turn, cause differences in the distribution of soil physical and chemical properties (Han et al., 2013).

The heterogeneity of these available resources at different locations in a gap might result in variation in regeneration density and growth within individual gaps (Denslow, 1980; Pickett and White, 1985; Powers et al., 2008; Kern et al., 2014). For example, Poznanovic et al. (2014) found that the southern edges of the largest gaps with a diameter of 2 H (H was the average canopy height) contained the highest abundance of yellow birch (*Betula alleghaniensis*) and eastern hemlock (*Tsuga canadensis*) per unit area, and they attributed this result to the distribution of moisture availability and shade tolerance of species. Wang et al. (2017a) investigated the short-term influences of canopy gap size on the growth and spatial patterns of Chinese pine regeneration and found that the maximum density of seedlings and saplings occurred mostly along the northeastern edges of gaps with a diameter less than 1.5 H. The heterogeneity of these available resources was thought to be a factor promoting the differences in the regeneration response in terms of the distribution and growth. However, there are few studies on the specific distribution of regeneration density and growth at different distances and across multiple azimuths from the center of a gap. Therefore, this paper focuses mainly on these issues by converting x/y coordinates of regeneration into different distances and directions from the center of each gap to further clarify the differences in location where regeneration occurred.

The main goal of this study was to better understand the spatial distribution of regeneration and the spatial autocorrelation of growth in gaps of Chinese pine plantations. To develop a spatially explicit relationship for regeneration, we created four size classes of gaps according to the average canopy height and recorded the detailed spatial location of regeneration in each gap. We tested the following hypotheses: H_1: the maximum density of regeneration will generally occur in the shaded region of border trees, whereas the best growth will occur in regions with light conditions; H_2: areas with sufficient light will be more conducive to the survival or preservation of regeneration, in other words, more extensive regeneration across a range of ages will occur in those areas; and H_3: regeneration growth will exhibit mutual inhibition in shaded areas as opposed to promotion in areas with sufficient light because of intra-specific competition for niche occupancy, moisture and nutrition.

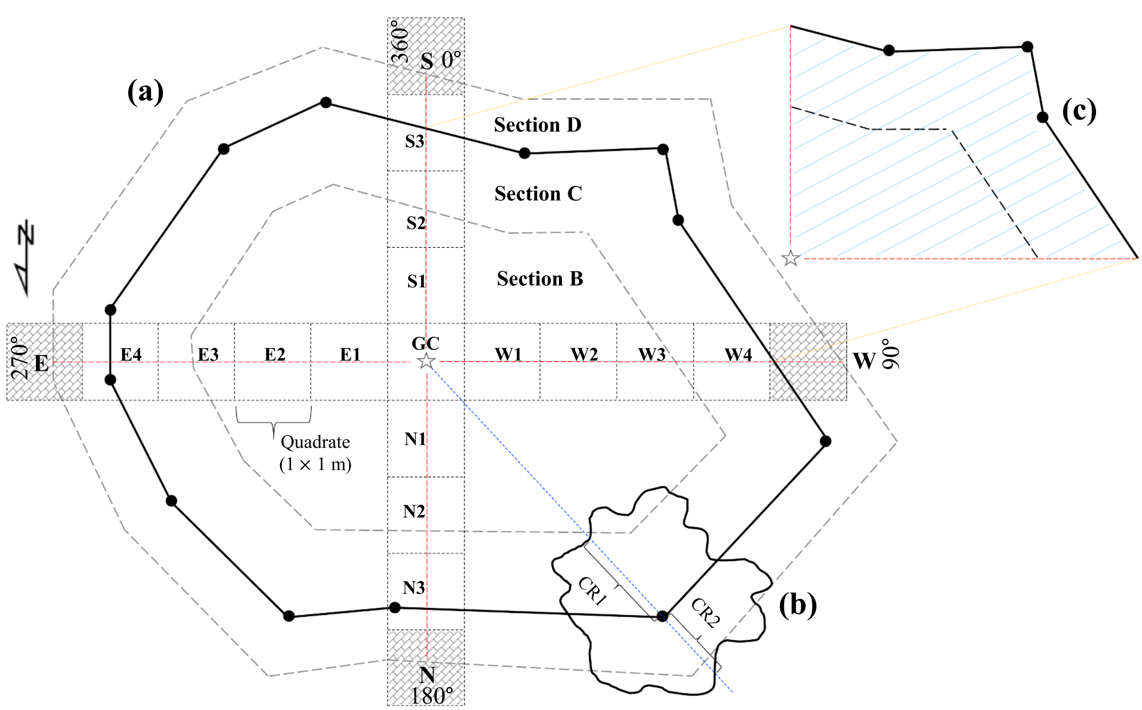

Fig. 1. Schematic of canopy gap 13 to show gap sections, gap aspects and strips with 1 × 1 m squares. (a) Diagram of three gap sections and two strips. (b) Measurement of the crown radius of border trees. (c) Diagram showing the partitioning of a gap with SW aspect [0, 90°). ☆ represents the gap center. ⬠ is the vertical projection of the border tree crown. —●— is the edge of the gap, and ● is the border tree at the edge of the gap. ▒ represents the 1 × 1 m square beyond the gap. The specific explanation of the graphics can be found in Section 2.3 of the materials and methods. The width of the strips was not proportional to the area of the gap; the diagram serves to show how the strips were established.