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Regeneration response to canopy gap size in a Chinese pine plantation: Species diversity patterns, size structures and spatial distributions

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ABSTRACT

Chinese pine (*Pinus tabuliformis* Carr.) is one of the most commercially important conifers in northern China because of its important economic and ecological value. However, most Chinese pine plantations have suffered degradation following fertility declines, pests and disease outbreaks. In this study, to evaluate whether gap creation can help achieve canopy recruitment for sustainable management, we analyzed the species diversity patterns of woody plant regeneration, growth status and the spatial distribution of Chinese pine regeneration in three control plots (C, 10×10 m) and four classes of gaps seven years after gap creation. The diameters of the gap classes were 1.00 (G-I, 10.0 m), 1.25 (G-II, 12.5 m), 1.50 (G-III, 15.0 m), and 1.75 (G-IV, 17.5 m) times the mean canopy height. There were no differences in diversity patterns between the tested gap sizes, between gaps and under the canopy, this finding may be attributed to trees and shrubs require a relatively long time to become established. Although gap size had no influence on the density of Total (all regeneration), it significantly decreased and increased the density of seedlings (height $\leq$ 100 cm) and saplings (height > 100 cm), respectively, along the gap size gradient, which likely resulted from the differences between these two categories of regeneration in terms of shade tolerance and resource requirements. Similarly, the height, ground diameter and height growth of Total, seedlings and saplings in the current year showed positive responses to gap size. All gap size classes showed approximately normal height and ground diameter distributions, with a longer tail toward larger individuals with greater gap sizes. These results suggested that Chinese pine can be managed by gap creation in plantations, especially when combined with gradual gap expansion. In addition, Total and seedlings showed mostly random patterns across all scales, with aggregation at smaller scales, and the percentage of random patterns of saplings was greater than that of seedlings for all gap sizes. These differences in spatial patterns may have been associated with the survival strategies of tree species and the density-dependent processes. Further monitoring and gap expansion will likely be required to determine the long-term efficacy of gap creation to ensure successful canopy recruitment and to maintain sustainable management.

1. Introduction

Due to the continuous decline in natural forest area likely caused by climate change, natural disasters and man-made damages, plantations play an irreplaceable role in providing large quantities of timber and non-timber forest products (Peng et al., 2008). However, some studies have indicated that plantations, especially coniferous plantations, are likely to encounter problems with regeneration and endanger long-term forest viability due to anthropogenic non-sustainable management practices or overexploitation (Hernández-Barrios et al., 2014; Zhou and Sheng, 2008). Chinese pine (*Pinus tabuliformis* Carr.) plantations have also suffered regeneration problems (Dong et al., 2013). Chinese pine is one of the main afforestation tree species in North China and has important roles in ecological construction and environmental protection. Therefore, we should pay close attention to gap-based cultivation strategies to balance production and sustainable ecosystem functions. Forest gaps are generally thought of as the result of frequently occurring small-scale disturbances in forest

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communities and are one of the important drivers for promoting vegetation succession and regeneration (Yu et al., 2005). Creating gaps not only provides places for species regeneration but also increases environmental heterogeneity for maintaining species diversity (Elias and Dias, 2009; Garbarino et al., 2012). Therefore, the aim of this study was to test the effect of gaps on the regeneration of Chinese pine plantations.

One of the problems with the regeneration of plantations is their consistently low species diversity (Coates and Burton, 1997). Several studies (McClure and Lee, 1993; Van Der Meer et al., 1999) have found that gap size is an important structural characteristic that determines the future species composition within gaps. These findings suggested that large gaps are generally beneficial for the regeneration of light-demanding plants, while smaller gaps commonly favor the regeneration of shade-demanding plants, and only a certain gap size can promote the coexistence and development of different shade-tolerant species (Ricklefs, 1977; Connell, 1978; Wang and Liu, 2011). Similarly, other studies have also demonstrated that environmental variables (such as light) become more dissimilar at gap positions as the gap size increases (the gap partitioning hypothesis), resulting in an increase in species diversity due to different species using alternative regeneration niches (Coates, 2002; Kumar and Ram, 2005). Conversely, Bolton and D'Amato (2011) and Hubbell et al. (1999) suggested that gap size dose not increase species diversity patterns, although it can promote the establishment and growth of regeneration. In addition, some changes, which were characterized by short-term increases after gap creation and then decreases with canopy closure, occurred in species diversity at different gap stages. These changes might be due to the transient increases resulting from the germination of heliophiles, which benefit from improved light conditions at the early stage of gap formation and subsequently decline due to species competition and resource limitation as the gap gradually closes (Li et al., 2010; Wang and Liu, 2011). Therefore, we should obtain a better understanding of whether gap creation influences woody plant species diversity in Chinese pine plantations.

In addition to the influence of gap creation on species diversity, determining whether the local species can successfully regenerate in plantations and grow to be dominant in the canopy is of critical importance (Taki et al., 2010). Wang and Liu (2011) studied the influence of gap creation on the regeneration of Chinese pine plantations and found that creating gaps not only influences the emergence and density of some local species but also lead these species to become dominant in gaps of 25–150 m^2 and 150–450 m^2. This finding was similar to the results of a study by Dong et al. (2013), who also tested the response of natural regeneration to gap size (4–40 m^2) in Chinese pine plantations and suggested that gaps could promote the density and growth of regeneration compared with those under the canopy. Other studies that have examined the effects of gap size on the regeneration of Chinese pine plantations have led to similar conclusions (Han et al., 2012; Li et al., 2012). However, the gaps in the studies mentioned above were primarily formed by natural disturbances (e.g., diseases, insect pests, or strong winds), making it difficult to determine the age of either the gaps, as a gap may have contained more than one gap-maker with different ages, or the gap-makers themselves. In our study, we created gaps with different sizes via group-selection cutting to determine the responses of the density and growth during regeneration. It is also critical to understand whether the dominant gap species exhibits the appropriate size structure to promote further successful regeneration (Wang and Liu, 2011). The size structure of regeneration can help reveal the persistence of species establishment and the continued recruitment ability of the community (Moktan et al., 2009). However, we still do not know whether the height (RH) or ground diameter (GD) structure of regeneration within gaps exhibit sustainable development.

Similar to the size distribution, the spatial pattern of regeneration has also been used to understand the dynamics of regeneration (Cordero et al., 2016). An analysis of the spatial pattern is helpful for better understanding the biological characteristics of a particular species (e.g., shade tolerance or intolerance), ecological processes (e.g., seed dispersal or intra- and inter-specific competition) (Perry et al., 2002; Wiegand and Moloney, 2004; Fang and Yu, 2016), and their relationship with environmental variables (Condit et al., 2000). Although the common method for studying the spatial pattern of regeneration is Ripley's K-function ($K(r)$), which is the expected number of points in a circle of radius r centered at an arbitrary point, the cumulative $K(r)$ confounds effects at larger distances with effects at shorter distances (Wiegand and Moloney, 2004). An alternative approach of using rings instead of circles, i.e., the O-ring statistic ($O(r)$), was employed in this study. $O(r)$ is a probability density function that represents the neighborhood density and is more intuitive than $K(r)$ (Wiegand and Moloney, 2004). $K(r)$ and $O(r)$ define the spectrum of spatial patterns that range from aggregation to random to dispersion. Aggregated spatial patterns are likely the result of environmental heterogeneity, edaphic patterns, seed dispersal patterns, gap colonization, and vegetative reproduction (Rozas and Prieto, 2000; Aldrich et al., 2003; Wolf, 2005). Random spatial patterns can arise under homogenous environmental conditions or after chance events, including zoochorous dispersion (Cordero et al., 2016) or short-term weather patterns (Poznanovic et al., 2014). Dispersed patterns are likely caused by density-dependent, competitive effects between individuals for a limited set of resources and by selective cutting or grazing (Moustakas et al., 2008; Poznanovic et al., 2014; Cordero et al., 2016; Janík et al., 2016). However, most studies of the spatial patterns of Chinese pine have focused on natural forests, and there are few studies on plantations, especially regeneration in plantations (Niu et al., 2008; Zhang et al., 2009, 2010). Therefore, a series of experiments were performed in a Chinese pine plantation to test the spatial patterns of regeneration in gaps with different size classes.

The main goal of this study was to estimate the effects of gap size on regeneration by creating four different gap size classes in a Chinese pine plantation. Specifically, we sought to address the following unknowns: (i) whether gap creation increases the species diversity of woody plants; (ii) whether gap creation favors the density and growth of Chinese pine regeneration; (iii) whether Chinese pine regeneration within the gaps exhibit changes in RH or GD structures with a decrease in the number of large individuals; and (iv) what the spatial patterns of Chinese pine regeneration are for different height classes (height $\leq$ 100 cm, seedlings; height > 100 cm, saplings). Based on these aims, we hypothesized that creating gaps in a plantation would not increase the species diversity of woody plants because consistently low species diversity is a characteristic of plantation ecosystems. Because creating gaps can provide spaces and improve the micro-environment in the gaps by increasing light availability and because Chinese pine is considered a heliophyte, we also hypothesized that gap creation could promote the establishment of regeneration and the growth of this species. However, competition and density-dependent mortality were predicted to increase in the gaps as the canopy closed again. Therefore, we predicted that Chinese pine regeneration in the gaps would not be able to achieve canopy recruitment if gap expansion was not performed. Finally, we predicted that seedlings would be mostly clustered but that saplings would be randomly distributed within the gaps based on the survival strategy of tree species that jointly resist external interferences during the first few years of their life and require more space and light to promote growth with increasing age.