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Converting larch plantations to mixed stands: Effects of canopy treatment on the survival and growth of planted seedlings with contrasting shade tolerance

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ABSTRACT

Larch (*Larix* spp.) plantations are important for timber production in Northeast China, but this monoculture practice has led to problems such as decreased soil fertility and water-holding capacity. To examine the possibility of gradually converting pure larch plantations to mixed stands by small-scale canopy regulation, we planted seedlings of two species with contrasting shade tolerance, light-demanding Manchurian walnut (*Juglans mandshurica* Maxim.) and shade-tolerant Korean spruce (*Picea koraiensis* Nakai), in larch plantations with four different canopy retention intensities (larger gap, 160 m^2; smaller gap, 45 m^2; thinning, 25% intensity based on basal area; and control, forest understory). After two growing seasons, we found that both species had higher survival rates and growth rates in larger gaps than in forest understories, but the detailed responses to treatments differed between species. Manchurian walnut responded strongly to larger gaps but insensitively to other treatments, especially with respect to biomass accumulation. In contrast, Korean spruce responded gradually with increasing canopy openness. However, canopy treatments had almost no effect on non-structural carbohydrate (NSC) concentration, biomass allocation, and NSC pool allocation, which only differed between species. Our findings indicated that the two species of contrasting shade-tolerance were able to survive and grow in larch plantations, and a small-scale canopy treatment, especially creating gaps of ~160 m^2 in size, could significantly improve seedling survival and growth during the first two years. Therefore, enrichment planting in conjunction with a low-intensity canopy regulation may play an effective role in converting larch plantations to mixed stands while maintaining continuous stand functions during the conversion process.

1. Introduction

Larches (*Larix* spp., mainly *L. olgensis* Henry and *L. keampferi* (Lamb.) Carr.) are important fast-growing commercial species in Northeast China, which have been widely planted for several decades to replace natural secondary stands to meet timber demands (Wang and Liu, 2001; Zhu et al., 2008). Currently, there are about 2.6 million ha of larch plantations in Northeast China (Liu et al., 2005; Yan et al., 2017). Although larch plantations play an essential role in timber supplies, such long-term monoculture practice leads to potential problems. Compared with the adjacent natural secondary stands, the larch plantations are facing reduced soil fertility. For example, after a conversion from natural secondary stands to larch plantations, soil organic carbon and soil microbial biomass declined significantly (Chen and Yin, 1990; Chen and Li, 2003; Wang and Wang, 2007; Yang et al., 2010). An increased evapotranspiration in larch plantations also decreased the soil water content (Yang et al., 2010), which could potentially alter hydrological cycle. Moreover, larch plantations may be more vulnerable to disease, pest insects, or other disturbances because of the homogeneous canopy structure (Xu et al., 2000; Li, 2004; Haughian and Frego, 2016) and show less self-recovery capability (Roberts, 2004; Zhu et al., 2010). Thus, there is an urgent need for improving the resource sustainability and ecological functions of larch plantation in Northeast China (Mason and Zhu, 2014).

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As forest management strategies shift from pursuing timber production to providing ecological services (Li and Zhou, 2000), the approach of "close-to-nature" silviculture is becoming increasingly popular. As a result, thinning and group harvesting are commonly used to emulate fine-scaled natural disturbances and provide suitable microenvironments for tree regeneration (York et al., 2004; Zhu et al., 2010; Hu et al., 2012; Knapp et al., 2013). Previous studies have considered promoting natural regeneration in larch plantation understories (Deal, 2007; Yan et al., 2013). For example, a thinning experiment assessed the possibility of converting even-aged larch (*L. olgensis*) plantations to uneven-aged stands and found that natural *L. olgensis* seedlings failed to survive the current year after germination under different thinning intensities, but some broadleaved tree species could establish successfully (Zhu et al., 2010). These results indicate that thinning intensities may limit natural larch regeneration (Liu, 1997; Wang and Zhang, 1990; Zhu et al., 2008), but it may be possible to convert pure larch plantations to mixed larch-broadleaved stands (Zhu et al., 2010). However, the natural regeneration of broadleaved species could be poor after several years even with thinning treatments (Lei et al., 2003), which may be a result of increased competition from herbs and shrubs (Man et al., 2009; Kern et al., 2013). In addition, treatment responses were not only related to light levels (Thomas et al., 1999) but also other environmental factors, such as disturbance history and stand spatial pattern (Lei et al., 2003). For example, larch plantations located on the downslope of secondary stands could be more feasible for the establishment of some broadleaved species whose seeds are more easily moved downslope (Yan et al., 2013). Animals such as rodents could also affect seed dispersal and then influence seedling establishment (Wang et al., 2017). Given the uncertainty of natural regeneration, a combined treatment of canopy manipulation and seedling planting may be required to establish target species in larch plantations.

Enrichment planting in conjunction with thinning or group harvesting may greatly shorten the time needed to convert pure plantations to mixed stands compared with natural regeneration (Paquette et al., 2006; Owari et al., 2015). Owari et al. (2015) monitored the height growth of planted Korean pine seedlings in larch stands with different strip-cut widths and found that seedling height increased in wider strips. However, a strong harvesting intensity or areas harvested may be critically restricted in some stands due to the requirement of continuously providing desired forest services, such as water resource conservation (Wang et al., 2013) and wildlife habitats (Knapp et al., 2013). Furthermore, competition from understory shrubs and herbs could increasingly restrain seedling growth as canopy removal intensities are increased (Paquette et al., 2006), which suggests that competition control measures may be needed during the early stage of seedling establishment (Kern et al., 2013). Growth response to canopy treatments also varied among different planting species (Kobe and Coates, 1997), which provides flexibilities of species selection to meet stand conditions and management objectives (Newsome et al., 2016). A long-term study assessed the effects of gap size on the survival and growth of three planted tree seedlings in mixed coniferous stands and found that both seedling survival and growth increased with gap size, but species-specific differences existed (Newsome et al., 2016). For example, the growth of Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) was less sensitive to increased gap size compared with lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (Newsome et al., 2016). Therefore, a combination of different planting species and canopy treatments may achieve a multiple-layer understory structure.

Seedling performance in the regeneration layer largely decides the extent to which the species can be used for planting. In addition to simple growth indicators such as height and diameter, carbohydrate storage could provide more knowledge on seedling adaption to different canopy environments. Non-structural carbohydrate (NSC) storage reflects the balance between carbon supply and demand (Sala et al., 2012). Seedlings with higher NSC storage may have more opportunities to survive extreme conditions such as shade (Kobe, 1997; Myers and Kitajima, 2007). Seedlings with different functional types could have different carbohydrate allocation strategies, which may contribute to the coexistence of different species (Zhang et al., 2013; Villar-Salvador et al., 2015). Some studies also reported that seedlings had plasticity and could trade off in disadvantageous stand conditions. For example, Sevillano et al. (2016) evaluated the biomass allocation of European beech (*Fagus sylvatica* L.) under different light intensities and found that seedlings allocated more biomass to above-ground growth in shaded environments. However, other studies claimed that the biomass allocation of European beech was not affected by light availability (Curt et al., 2005) but mostly by ontogenic traits (Van Hees and Clerkx, 2003). The inconsistent results indicate that factors affecting seedling performance may differ among sites with different stand conditions, and intra- or inter-specific differences may also result in different outcomes.

The objective of our study was to evaluate the possibility of converting pure larch plantations to mixed stands through enrichment planting under low-intensity canopy treatments. We selected two local tree species, Manchurian walnut (*Juglans mandshurica* Maxim.) and Korean spruce (*Picea koraiensis* Nakai). Manchurian walnut is a dominant broadleaved light-demanding species in Northeast China. It is also a commercial species and has important medicinal values. Korean spruce is a coniferous shade- and drought-tolerant species, which is distributed in most natural stands in Northeast China. We expected that Manchurian walnut and Korean spruce seedlings would coexist in the regeneration layer and gradually develop into different canopy layers due to their different growth characteristics. Our specific objectives were to (1) compare seedling survival and growth in response to different canopy treatments; (2) compare seedling strategy of carbohydrate storage allocation in response to different canopy treatments; and (3) find a minimal intensity but effective canopy treatment approach which could promote the regeneration of these two seedling species with contrasting shade tolerance in larch plantations.

2. Methods

2.1. Study site

Our study was carried out in Qingyuan Forest, one of the Chinese Ecosystem Research Network (CERN) sites established by the Chinese Academy of Sciences. The study area is located in a mountainous region of Liaoning Province, Northeast China (41°51′N, 124°54′E, 500–1100 m above sea level). It has a temperate continental monsoon climate, with a warm and humid summer and a dry and cold winter. The mean annual air temperature is between 3.9 °C and 5.4 °C, with the coldest month of January averaging −12.1 °C and the warmest month of July averaging 21.0 °C. The annual precipitation is 811 mm, 80% of which falls during the summer. The frost-free period is 130 days, with the first frost in early October and the last frost in late April. The soil is a typical brown soil (25.6% sand, 51.2% silt, and 23.2% clay) which belongs to Udalfs according to the US Department of Agriculture soil taxonomy (second edition) (Yang et al., 2013). The soil thickness ranges from 30 cm to 60 cm (Zhu et al., 2008). The mean soil pH of 0–5 cm in larch plantations is 5.4. The soil total carbon in 0–5 cm is 43.7 g kg^{-1}. The soil organic matter in 0–5 cm includes 73% heavy fraction carbon, 13.7% light fraction carbon and 13.8% mineralizable carbon (Yang et al., 2013). More detailed soil characteristics are shown in Yang et al. (2013).

Historically, the area was covered by mixed broadleaved-Korean pine stands. However, decades of unregulated timber exploitation severely disrupted the forest ecosystems, and more than 70% of the stands became secondary stands, with almost no remaining Korean pine trees. Since the 1950s, larch has been extensively planted in patches to replace secondary stands to meet the growing timber demands as it is a fast-growing commercial species. Currently, natural secondary stands