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Spatial structure of timber harvested according to structure-based forest management

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ABSTRACT

The selection of harvested trees is key to the success of near-natural forest management, yet few people have focused on the structural characteristics of harvested woods. Here, we examined the structural characteristics of harvested trees in Korean pine-broadleaf forest and pine–oak mixed forest in China using bivariate distributions of spatial structure parameters and the distribution of diameter classes. The stands were strictly managed according to the principles of structure-based forest management. We found that trees cut from both types of forest had wide structural diversity: they were widely distributed across vertical levels of the forest stand, including dominant, medium, and suppressed trees. Most trees from the Korean pine-broadleaf forest were of small–medium size and were highly mixed and randomly distributed in relation to their neighbors. In contrast, trees cut from pine–oak mixed forest tended to be clumped in relation to their neighbors. The majority were dominant trees surrounded by other species or distributed randomly, and were generally evenly distributed across stem diameters. In both forest types, most individuals were highly mixed and distributed in a random pattern, and trees in a clumped or regular distribution were more likely to be retained. In addition, the distribution of diameter at breast height size classes retained a reversed-J-shaped curve before and after management. These structural features closely matched the prior conditions of both forests and the purpose of management. They may also be conducive to quick selection of trees cut from the same forest type in the future, and can aid the recognition and interpretation of forest structure.

1. Introduction

Secondary forests developing into sub-climax or climax vegetation communities under natural conditions go through several developmental stages. Artificial cultivation can promote forest development, which may shorten the formation time of a target stand (Kint, 2005; Kang, 2011; Shen and Zhai, 2011). Management to speed the development of a forest stand to a more diverse, natural condition has become an international trend (e.g., Kuuluvainen, 2002; Kuuluvainen et al., 2002). Stand complexity typically refers to abundant species diversity and the presence of trees in two or more age classes. Near-natural forest management (NNFM) aims to develop a structure similar to that of the original forest. Under this method, trees of different ages and sizes are distributed in the same stand, new trees are established through natural recruitment, and timber harvest takes place selectively throughout the forest stand. This method is increasingly accepted internationally because it focuses on ecological and environmental feasibility (O'Hara, 2001, 2007).

Selective cutting is an important component of NNFM. It is theoretically based on the natural forest process of self-thinning. Cutting a single tree or small group in a limited area creates a gap that can improve understory light conditions, promote the growth of seedlings and young trees, and alter the composition of plant species and structural diversity, forming more habitats for species coexistence and the conservation of biodiversity (cf. Suo et al., 2004; Walters, 2005; Wang and Liu, 2011). However, typical primary concerns in forestry are the amount of timber obtained from selective felling (e.g., Mäkinen and Isomäki, 2004), changes in forest stand structure or composition (e.g., Pfister et al., 2007; Weiskittle et al., 2011), growth increments (e.g., Cassidy et al., 2012), non-timber forest products (e.g., Bonet et al., 2012), and forest microenvironmental conditions (e.g., Cogliastro and Paquette, 2012; Grayson et al., 2012). The structural characteristics of cut wood are rarely focused on, although they are sometimes considered, in NNFM. For example, the objective of harvesting in single-species stands is more suitable for dominant individuals or compressed

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woods. In mixed forests, the focus is typically on desirable timber species, the distance to and species composition of surrounding trees, and mechanisms that may affect tree growth or quality, such as shade, shelter, interspecific competition, and inhibition. Quantifying the structural features of cut forests may help to elucidate and promote better forest management.

Tree size, distributional pattern, and species composition are the primary structural properties considered in forest management (cf. Kint et al., 2000; Kint, 2005). They directly include interspecific and intraspecific competition, seedling recruitment, and tree growth, and are indirectly affected by the utilization of environmental resources by animals and plants. The management of tree size is a key factor in traditional harvest management and support of forest cultivation (Graz, 2008). Without disturbance, a multi-age managed or natural forest with a diverse size structure tends to show gradually increasing diameter classes in a histogram of sizes, resulting in a reversed-J shape (i.e., negative exponential distribution), which is considered suitable for sustainable management (e.g., Aldrich et al., 2005; Piovesan et al., 2005; Hart et al., 2008). A balanced reversed-J curve allows calculation of the ideal number of trees in each size class and determination of a balanced size structure for unevenly aged forests. Such structural characteristics can be maintained after selective thinning and many unevenly aged forests around the world are managed according to the desired distribution of diameter classes (Pukkala et al., 2009). However, timber management is unlikely to achieve an ideal diameter distribution because it has little basis in biological theory or economic incentives (Westphal et al., 2006; Gadow et al., 2012). In addition, when applied to large areas, it usually results in the simplification and homogenization of forest structure at the landscape level (O'Hara, 2007). Another obvious shortcoming is that the assessment of tree size alone, without consideration of species diversity and distribution, does not meet the structural information requirements of NNFM. Although the abundance of tree species, age structure, and relative size proportions may be considered in such practices, they do not incorporate spatial structure, which is an important feature of forest stand structure. Although many practices have attempted to adjust tree distribution patterns, most have used qualitative numerical indices, rather than distributional patterns (Hui et al., 2007, 2010). The application of spatial structure indices for stand structure in forest management remains rare (Kang, 2011).

Precise adjustment of the spatial distribution of forest stands has recently become possible through the improvement of structural parameters, such as the uniform angle index (W), tree species mingling (M), and dominance (U) (Gadow, 1993; Hui and Gadow, 2003; Hui et al., 2007; Mason et al., 2007; Laarmann et al., 2009; Pommerening et al., 2011; Li et al., 2012; Petritan et al., 2012). The combination of these structural parameters can express spatial relationships of mixture and size differentiation between a reference tree i and its four nearest neighbors. After determining a target structure, often in reference to natural forest stands, spatial relationships can be gradually managed to improve the diversity and health of a forest stand. Spatial relationships among neighboring trees are easily identified, providing marked operational flexibility in spatial structure adjustment (Hu and Hui, 2006; Hui et al., 2010; Li et al., 2012; Gao et al., 2013; Pastorella and Paletto, 2013). In this paper, we present the structure-based forest management (SBFM) method, an extension of NNFM that utilizes spatial relationships among a target individual and its four nearest neighbors. The goal of this method is to use single tree selection and other methods to accelerate stand development toward high species diversity, random distribution, and size differentiation of a healthy and stable forest, while simultaneously valuing timber production.

Korean pine-broadleaf and pine–oak mixed forests are typical vegetation types in northern China, where they play important ecological and economic roles. Although many forests have sustained different degrees of historical damage, large areas of natural secondary forest have formed after decades of protection (Zhao et al., 2009; Hui et al., 2010; Li et al., 2012), and the core area of the Changbai Mountain Nature Reserve has a small amount of virgin forest (Hao et al., 2007). To dynamically monitor the successional processes of Korean pine-broadleaf and pine–oak mixed forests, and to investigate the positive effect of SBFM on forest communities, we established eight long-term plots in two forest types and managed four of them to gradually progress toward a high level of mixture and random distribution, as a demonstration of SBFM. Using multiple parameters, we began to modify the spatial structure of both forest types in 2008–2010. The goal was to improve the health of both forest types while utilizing mature trees with target diameters at breast height (DBHs) in pine–oak forest. The purposes of this paper are: (1) to introduce the main theories and practical application of SBFM; (2) to quantify and summarize the structural characteristics of forests harvested according to SBFM; (3) and to explore the structural differentiation of harvested stands between different forest types.

2. Materials and methods

2.1. Study areas

We used two study areas of two different types of natural forest (Korean pine-broadleaf forest and pine–oak mixed forest) in China (Fig. 1). The Korean pine-broadleaf forest covers 31,562 ha in the Dongdapo Natural Reserve near Qianjin Village, Jilin Province. It is located at low altitude (200–800 m) on Zhangguangcai Mountain, approximately 45 km from Jiaohe City, in a monsoon climatic region with dry, windy springs and warm, wet summers. Mean annual rainfall is 700–800 mm, occurring primarily between June and August. The relative humidity is 75% and total evaporation capacity is >1000 mm. The frost-free period is approximately 120–150 days. The mean annual temperature is 3.5 °C and the minimum temperature is −22.2 °C in deep winter, when 1.5–2.0 m snow accumulates. Dark-brown forest soil is formed under the combined influences of heat and moisture in mixed forests. The study site was located in the 52nd sub-compartment (127° 35′–127° 51′E, 43° 51′–44° 05′N), where the topography is flat and the aspect is slightly toward the northwest. This region historically belonged to the trial forest farm of Jilin Forestry College, and thus only a small portion was subject to different degrees of disturbance, followed by complete restoration, gradually forming a highly mixed stand dominated by *Pinus koraiensis* Sieb. and Zucc., *Abies holophylla* Maxim., *Abies nephrolepis* Maxim., and *Picea jezoensis* var. *microsperma*. The crown density is 0.9 and average tree height is approximately 13.5 m (cf. Xu et al., 2006; Li et al., 2012, 2014).

Close to the west end of the Qinling Mountains, the pine–oak mixed forest site was located on the Baihua tree farm in the 57th compartment on Xiaolong Mountain, Gansu Province (104° 22′–105° 43′E, 33° 30′–34° 49′N). This site is in the transitional region between the warm temperate and northern subtropical zones. It is characterized by distinct seasonal variation, with wet springs and autumns, hot summers, and temperate winters. Annual rainfall is 460–800 mm and approximately 70–80% of it occurs between July and September, although significant annual variation occurs, with wet years having twice the rainfall of dry years. Annual evaporation is 989–1658 mm and relative humidity is 68–78%. The annual average temperature is 7–12 °C, with a range from −23.2 °C to 39.2 °C. Annual hours of sunshine range from 15:20 to 23:13 and the frost-free period ranges from 120 to 218 days. The terrain is flat, with an average elevation of 1720 m. The soil is mountain brown loam, which has a high organic content and thickness of 30–60 cm. The soil pH is 6.5–7.5 and the site is well drained (Suo et al., 2004; Wang