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Effects of Logging Intensity on Structure and Composition of a Broadleaf-Korean Pine Mixed Forest on Changbai Mountains, Northeast China

WU Zhijun[1, 2, 3], SU Dongkai[4], NIU Lijun[5], Bernard Joseph LEWIS[1], YU Dapao[1], ZHOU Li[1], ZHOU Wangming[1], WU Shengnan[1, 3], DAI Limin[1]

(1. *State Key Laboratory of Forest and Soil Ecology*, *Institute of Applied Ecology*, *Chinese Academy of Sciences*, *Shenyang* 110016, *China*; 2. *Liaoning Technical University*, *Fuxin* 123000, *China*; 3. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*; 4. *Jilin Forest Industry Group Limited Liability Company*, *Changchun* 130021, *China*; 5. *Changbai Mountains Academy of Sciences*, *Antu* 133613, *China*)

Abstract: In order to identify a harvesting model which is beneficial for broadleaf-Korean pine mixed forest (BKF) sustainability, we investigated four types of harvested stands which have been logged with intensities of 0 (T_0, control), 15% (T_1, low intensity), 35% (T_2, moderate intensity), and 100% (T_3, clear-cutting), and examined the impacts of logging intensity on composition and structure of these stands. Results showed that there were no significant differences between T_0 and T_1 for all structural characteristics, except for density of seeding and large trees. The mean diameter at breast height (DBH, 1.3 m above the ground), stem density and basal area of large trees in T_2 were significantly lower than in T_0, while the density of seedlings and saplings were significantly higher in T_2 than in T_0. Structural characteristics in T_3 were entirely different from T_0. Dominant tree species in primary BKF comprised 93%, 85%, 45% and 10% of the total basal area in T_0, T_1, T_2 and T_3, respectively. Three community similarity indices, the Jaccard′s similarity coefficient (C_J); the Morisita-Horn index (C_{MH}); and the Bray-Curtis index (C_N), were the highest for T_0 and T_1, followed by T_0 and T_2, and T_0 and T_3, in generally. These results suggest that effects of harvesting on forest composition and structure are related to logging intensities. Low intensity harvesting is conductive to preserving forest structure and composition, allowing it to recover in a short time period. The regime characterized by low logging intensity and short rotations appears to be a sustainable harvesting method for BKF on the Changbai Mountains.

Keywords: broadleaf-Korean pine mixed forest; forest structure; species composition; logging intensity; Changbai Mountains

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1 Introduction

Broadleaf-Korean pine mixed forest (BKF) is the original vegetation type on the Changbai Mountains in Northeast China. It has provided large amounts of timbers as is well-known for remarkable ecological functions (Dai *et al*., 2004). However, after years of extensive logging, the composition and structure of primary BKF have been damaged, and the forests have been degraded (Wang *et al*., 2011; Zhao *et al*., 2014).

Harvesting is one of the most important activities in forest management. Different types of harvesting practices can directly or indirectly influence forest structure, composition, species diversity (Widayati and Carlisle,

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Corresponding author: DAI Limin. E-mail: lmdai@iae.ac.cn

2012), regeneration (Wagner *et al*., 2011), and the microclimate (Cheng *et al*., 2014). After years of exploration, selective harvesting has been demonstrated to be a more appropriate method for BKF sustainable management (Yu *et al*., 2011). Over the past, scholars researched the effects of selective harvesting on survivor growth, simulated forest resource dynamics under various logging intensities (Shao *et al*., 1994; Yu *et al*., 2001; Shao *et al*., 2006; Xie *et al*., 2011), but most of these works took consideration in timber production and volume restoration, few studies have examined how forest structure and species composition respond to different logging intensities.

Ecosystem function depends on its structure and composition (Larsen *et al*., 2005). Forest structure and composition restrict both timber value and forest ecosystem stability (Shao *et al*., 1994; Dai *et al*., 2004).The lack of knowledge regarding effects of logging intensity on forest structure and species composition is one of the major problems encountered in developing plans for sustainable utilization of forest resources in the region.

In this study, we compared the impacts of different logging intensities on stand structure and tree species composition with the goal of identifying a sustainable harvesting model for BKF on the Changbai Mountains, and this is an essential step for sustainable utilization of this distinctive vegetation.

2 Materials and Methods

2.1 Study area and site selection

This study was carried out in forests (42°20′–42°40′N, 127°29′–128°02′E) administered by the Lushuihe Forestry Bureau (Fig. 1), which is located on the northwest-facing slope of the Changbai Mountains. The elevation of the study area ranges from 450 m to 1400 m. The area is characterized by a temperate continental climate, with cold, windy winter and wet summer. Mean annual temperature and precipitation are 2.9℃ and 894 mm, respectively. The soil is classified as dark brown forest soil. The climax vegetation is the BKF, in which dominant tree species include Korean pine (*Pinus koraiensis*), Amur linden (*Tilia amurensis*), Manchurian ash (*Fraxinus mandshurica*), Mongolian oak (*Quercus mongolica*), Mono maple (*Acer mono*).

We used satellite imagery, forest-inventory records, maps of logging history, and reconnaissance visits to identify forest stands that were believed to have been similar before harvesting. Four forest stands were selected and considered for this study as ′harvesting treatments′ (Fig. 1). The harvesting treatments included: 1) a primary forest or control treatment which at the

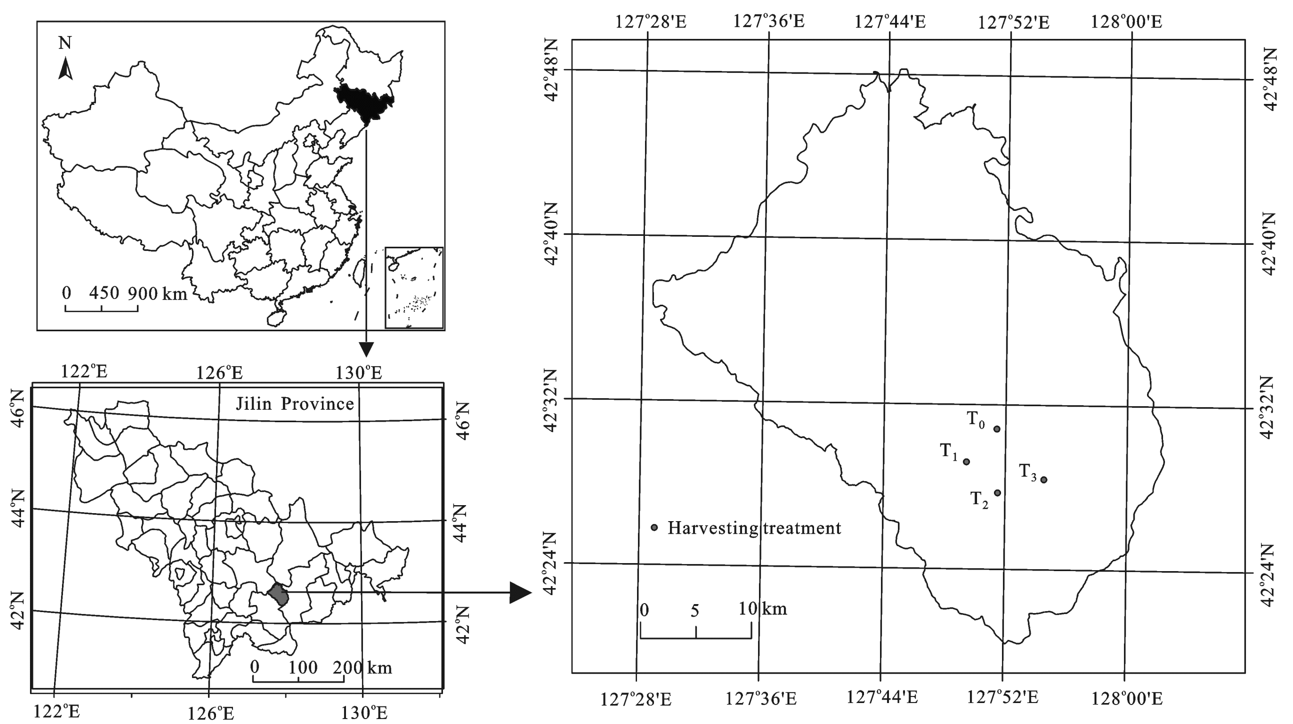

Fig. 1 Location of four harvesting treatments in study area

time of the study had no record of logging (T_0); 2) a low-intensity harvesting treatment, in which the primary forest had been logged with a logging intensity of 15% by volume (T_1); 3) a moderate intensity harvesting treatment, in which the primary forest had been logged with a logging intensity of 35% by volume (T_2); and 4) a clear-cutting treatment, in which all trees had been removed (T_3). Intervals between harvests and plot establishment were 9 years, 21 years and 29 years for T_1, T_2 and T_3, respectively. The dominate tree species are *Pinus koraiensis*, *Tilia amurensis*, *Quercus mongolica* and *Acer mono* in T_0; *Pinus koraiensis*, *Tilia amurensis*, *Quercus mongolica*, *Fraxinus mandshurica*, and *Acer mono* in T_1; *Pinus koraiensis*, *Populus davidiana*, *Salix matsudana* and *Acer mono* in T_2; *Betula platyphylla*, *Larix olgensis* and *Fraxinus mandshurica* in T_3, respectively.

2.2 Field sampling and measurement

We conducted this work based on Forestry Standards ′Observation Methodology for Long-term Forest Ecosystem Research′ of China (LY/T 1952–2011). Six 40 m × 40 m plots were established within each of the four harvesting treatment areas. Each plot was located at least 150 m from the forest edge and separated by at least 100 m from other plots. All plots were located on gentle slopes (< 5°), at an elevation of approximately 750 m. In each plot, species were identified and diameters were measured for all trees at least 2 cm in diameter at breast height (DBH, 1.3 m above the ground). Within each plot, we set four random 5 m × 5 m quadrats to census seedlings (< 2 cm DBH, ≥ 50 cm tall). Tree species were classified into three groups based on their shade tolerance: shade tolerant species (ST), mid-tolerant species (MD), and pioneer species (Pioneer). Tree data were grouped into three size classes: large trees (≥ 30.0 cm DBH), poles (10.0−29.9 cm DBH), and saplings (2.0−9.9 cm DBH) (Su *et al*., 2010).

2.3 Data analysis

To compare stand structure, the mean DBH, tree density and basal area of all species were calculated for saplings, poles, large trees and overall trees (≥ 2 cm DBH) in each treatment area. The density of seedlings was also calculated. When all plots for each treatment were combined, the diameter size distributions (in 5 cm diameter classes) among treatments were examined in order to reveal if the diameter range and the reverse-J shape of the diameter distribution curve, characteristic of primary forests, had been changed due to logging.

To assess differences in species composition between T_0 and the other three harvesting treatments, three indices were calculated (Magurran, 2004): the Jaccard′s similarity coefficient (C_J); the Morisita-Horn index (C_{MH}); and the Bray-Curtis index (C_N). Indices were compiled for seedlings, saplings, poles, large trees and overall trees using EstimateS software (Colwell, 2006).

Jaccard′s similarity coefficient (C_J):

$$C_J = \frac{c}{a+b-c} \tag{1}$$

where c is the number of species in sample A and sample B, a is the number of species in sample A, b is the number of species in sample B.

Morisita-Horn index (C_{MH}):

$$C_{MH} = \frac{2\sum a_j \times b_j}{(d_a + d_b)(N_a \times N_b)} \tag{2}$$

where N_a is the number of individual in sample A, N_b is the number of individual in sample B, a_j is the number of individual in the jth species in sample A, b_j is the number of individual in the jth species in sample B.

$$d_a = \frac{\sum a_j^2}{N_a^2} \tag{3}$$

$$d_b = \frac{\sum b_j^2}{N_b^2} \tag{4}$$

Bray-Curtis index (C_N):

$$C_N = \frac{2\,{}_jN}{N_a + N_b} \tag{5}$$

$${}_jN = \sum \min(a_j, b_j) \tag{6}$$

Differences among treatments in mean DBH, basal area, stem density and community similarity indices were assessed using one-way analysis of variance (ANOVA), followed by Tukey tests. Since there were no trees ≥ 30 cm DBH in T_3, stand structural characteristics in this diameter class were compared only among T_0, T_1 and T_2. Normality and homogeneity of variance of the residuals were tested and data were log-transformed if homogeneity of the variance was not met. A series of two-sample Kolmogorov-Smirnov tests was used to compare diameter class distribution between T_0 and the other three harvesting treatments. All statistical analysis was conducted using the software R (R Development Core Team, 2004).

3 Results

3.1 Stand structure

All stand structural characteristics, mean DBH, basal area and stand density, differed significantly among the four harvesting treatments (Table 1). The mean DBH of overall trees was significantly higher in T_0 and T_1 than that in T_2 and T_3, although the mean DBH of saplings and poles did not differ obviously among these treatments. The mean DBH of large trees was significantly higher in T_0 and T_1 than in T_2 (Table 1).

There were no significant differences between T_0 and T_1 for mean basal area of saplings, poles, large trees and overall trees. The mean basal area of saplings and overall trees was lower and higher, respectively, in T_0 and T_1 than in T_2 and T_3. The mean basal area of poles was obviously higher in T_3 than in the other three treatments. The mean basal area of large trees was significantly lower in T_2 than in T_0 and T_1 (Table 1).

Overall tree density was similar in T_2 and T_3, and these values significantly exceeded those in T_0 and T_1. Seedlings were significantly less abundant in T_0 than in the other three treatments. Saplings were significantly more abundant in T_2 and T_3 than in T_0 and T_1. Poles were significantly more abundant in T_3 than in the other three treatments. Large trees were significantly more abundant in T_0 than in T_1 and T_2 (Table 1).

When data for all plots in each treatment area were combined, the reverse-J diameter distribution curves were produced for T_0, T_1, and T_2, while a bimodal distribution was generated for T_3 (Fig. 2). The two-sample Kolmogorov-Smirnov test showed that the diameter class structure in T_3 differed significantly from that in T_0 ($K_D = 0.708$, $P < 0.05$). In contrast, there was no significant difference between T_0 and T_1 in terms of diameter class structure ($K_D = 0.375$, $P = 0.210$), and a similar diameter distribution was also revealed between T_0 and T_2 ($K_D = 0.296$, $P = 0.507$). However, with respect to the lower diameter classes, 80% of the trees in T_2 were lower than 10 cm DBH, while in T_0 and T_1 the corresponding values were 59% and 66%, respectively. With respect to the higher diameter classes, 1% of the trees in T_2 were greater than 50 cm DBH, whereas in T_0 and T_1 the corresponding values were 8% and 5%, respectively.

Table 1 Structural characteristics (mean ±S.E.) in four harvesting treatments

Parameter	Harvesting treatment				ANOVA
	T_0	T_1	T_2	T_3	
Mean DBH (cm)					
Sapling	4.6±0.1	4.5±0.2	4.8±0.2	4.3±0.2	NS
Pole	16.2±0.3	16.4±0.2	15.5±0.6	16.7±0.2	NS
Large tree	47.7±1.2a	45.8±1.0a	43.5±0.7b		***
Overall tree	13.8±0.7a	13.1±0.9a	8.8±0.7b	9.7±0.3b	***
Basal area (m^2/ha)					
Sapling	1.4±0.2b	1.2±0.1b	3.1±0.4a	2.1±0.2a	***
Pole	5.5±0.5b	6.0±0.3b	5.5±0.4b	19.3±0.6a	***
Large tree	31.6±1.3a	23.5±2.3a	15.5±3.0b		**
Overall tree	38.5±1.2a	30.7±2a	24.1±2.4b	21.4±0.7b	***
Density (trees/ha)					
Seedling	6061±469b	8028±705a	9856±705a	9946±746a	***
Sapling	579±88b	695±63b	1419±159a	1083±82a	***
Pole	238±18b	257±14b	265±21b	835±27a	***
Large tree	170±5a	108±13b	96±18b		**
Overall tree	987±78b	1060±67b	1780±143a	1918±91a	***

Notes: a, identical letters within a row indicate that means were similar ($P < 0.05$, Tukey test); $n = 6$ for all means of saplings 2.0–9.9 cm DBH, poles 10.0–29.9 cm DBH, large trees ≥ 30.0 cm DBH and overall trees ≥ 2.0 cm DBH; $n = 24$ for mean of seedlings < 2.0 cm DBH, ≥ 50.0 cm tall. NS: treatment effect is not significant. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

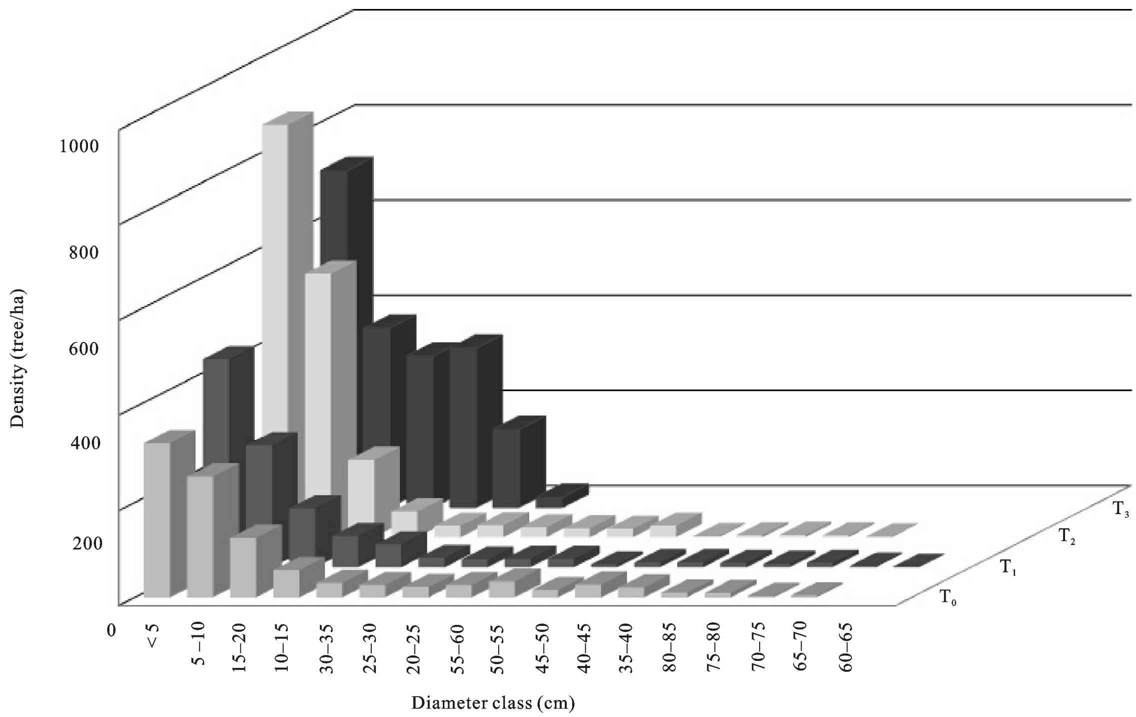

Fig. 2 Diameter at breast height (DBH) class distributions of trees ≥ 2 cm DBH for four harvesting treatments. T_0, primary forest as control; T_1, low-intensity harvesting treatment; T_2, moderate intensity harvesting treatment; T_3, clearcutting treatment

3.2 Species composition and similarity

For each harvesting treatment, the predominant pattern of species contributions to total basal area were as follows: T_0, six species contributed 93% of the basal area, including one pioneer species (14%), one MD species (7%) and four shade tolerant species (72%); T_1, seven species contributed 92% of the basal area, including one pioneer species (10%), two MD species (15%) and four shade tolerant species (67%); T_2, eleven species contributed 92% of the basal area, including four pioneer species (32%), three MD species (16%) and four shade tolerant species (44%); and T_3, five species contributed 92% of the basal area, including two pioneer species (79%), two MD species (10%) and one shade tolerant species (3%) (Table 2).

The three indices, C_J, C_{MH}, C_N, were significantly different among the four harvesting treatments (Table 3). Each of the three indices for saplings, poles, large trees and overall trees was significantly higher for T_0 and T_1 than for T_0 and T_2, and these indices for seeding did not differ obviously between the two pairs. All indices for T_0 and T_1 were significantly higher than for T_0 and T_3. The three indices for T_0 and T_2 were higher than for T_0 and T_3, in generally (Table 3).

4 Discussion

4.1 Effects of logging intensity on forest structure

Previous studies demonstrated that selective harvesting dramatically altered forest structure (Gu and Dai, 2008, Su *et al*., 2010). While in this study, effects of harvesting on stand structure vary with different logging intensities. Approximately nine years after the low intensity harvesting treatment (T_1) was applied, mean DBH, basal area and stand density of saplings, poles, large trees and overall trees, as well as the reverse-J diameter distribution, were similar between T_1 and T_0 (Table 1 and Fig. 2). For the moderate intensity harvesting treatment (T_2) logged 21 years before, the mean DBH, stem density and basal area of large trees were all significantly lower than those for T_0, while the numbers of seedlings and saplings were significantly higher (Table 1). Almost three decades had elapsed since clear-cutting was applied in T_3, and all structural characteristics were significantly different between T_3 and T_0 (Table 1 and Fig. 2). These results reflect that low intensity harvesting has little impact on forest structure, echoing the findings of McDonald *et al*. (2008). On the contrary, moderate intensity harvesting alters forest structure significantly (Su

Table 2 Tree species comprising 90% of total stand basal area in four harvesting treatments (DBH ≥ 2 cm)

Harvesting treatment	Tree species	Shade tolerance	Basal area (m^2/ha)	Percentage of total basal area (%)
T_0	*Pinus koraiensis*	ST	16.5	42.9
	Tilia amurensis	ST	7.1	18.4
	Quercus mongolica	Pioneer	5.3	13.8
	Fraxinus mandshurica	MD	2.6	6.8
	Acer pseudo-sieboldianum	ST	2.5	6.5
	Acer mono	ST	1.7	4.4
	Other species		2.8	7.2
T_1	*Pinus koraiensis*	ST	12.2	39.7
	Tilia amurensis	ST	3.4	11.1
	Quercus mongolica	Pioneer	3.0	9.8
	Fraxinus mandshurica	MD	2.6	8.5
	Acer pseudo-sieboldianum	ST	2.6	8.5
	Acer mono	ST	2.3	7.5
	Ulmus japonica	MD	2.0	6.5
	Other species		2.6	8.4
T_2	*Pinus koraiensis*	ST	5.1	21.2
	Populus davidiana	Pioneer	3.9	16.2
	Acer mono	ST	2.2	9.1
	Salix matsudana	Pioneer	1.8	7.5
	Tilia amurensis	ST	1.7	7.1
	Ulmus japonica	MD	1.7	7.1
	Abies nephrolepis	ST	1.6	6.6
	Juglans mandshurica	MD	1.2	5.0
	Fraxinus mandshurica	MD	1.0	4.1
	Betula platyphylla	Pioneer	1.0	4.1
	Quercus mongolica	Pioneer	0.9	3.7
	Other species		2.0	8.3
T_3	*Betula platyphylla*	Pioneer	14.3	66.8
	Larix olgensis	Pioneer	2.6	12.1
	Fraxinus mandshurica	MD	1.5	7.0
	Ulmus japonica	MD	0.7	3.3
	Pinus koraiensis	ST	0.7	3.3
	Other species		1.6	7.5

Notes: ST: shade tolerant species; Pioneer: pioneer species; MD: mid-tolerant species

et al., 2010; Zhang *et al*., 2013). The reason might be that, compared to the low intensity treatment, moderate intensity harvesting removes more canopy trees and changes forest structure by producing canopy openings, in the process triggering a rapid increase in recruitment into the seedling and sapling layers (Hall *et al*., 2003; Okuda *et al*., 2003). Not surprisingly, clear-cutting thoroughly alters forest structure by removing all vegetation (Grandpre *et al*., 2000).

Moreover, variations in total basal area mirrored differences in forest timber volume among treatments (Xie *et al*., 2011). Given that restoration time for the low intensity treatment (T_1) was shorter than that for T_2 and T_3, and also that the total basal area of T_1 was more similar to that of T_0 than were basal areas for the other two treatments (Table 1), it is reasonable the forest logged with low intensity would take less time to recover its pre-harvest volume than the others (Shao *et al*., 2006). Therefore, low-intensity harvesting can be combined with short cutting cycle in forest management,

Table 3 Jaccard′s similarity coefficient, Morisita-Horn index and Bray-Curtis index (mean ± S.E.) for four harvesting treatments

Parameter	Harvesting treatment			ANOVA
	T_0 and T_1	T_0 and T_2	T_0 and T_3	
Jaccard′s similarity coefficient (C_J)				
Seedling	0.30±0.03a	0.27±0.03ab	0.19±0.05b	*
Sapling	0.61±0.03a	0.47±0.04b	0.44±0.03b	*
Pole	0.56±0.03a	0.36±0.02b	0.37±0.03b	***
Large trees	0.63±0.04a	0.35±0.01b		***
Overall tree	0.73±0.03a	0.56±0.02b	0.51±0.02b	***
Morisita–Horn index (C_{MH})				
Seedling	0.43±0.04a	0.36±0.03a	0.11±0.04b	***
Sapling	0.72±0.04a	0.31±0.04b	0.20±0.02c	***
Pole	0.85±0.04a	0.36±0.06b	0.20±0.06c	***
Large tree	0.88±0.01a	0.35±0.06b		***
Overall tree	0.82±0.03a	0.36±0.03b	0.29±0.03b	***
Bray-Curtis index (C_N)				
Seedling	0.34±0.03a	0.28±0.02a	0.12±0.03b	***
Sapling	0.58±0.03a	0.31±0.03b	0.24±0.02b	***
Pole	0.66±0.03a	0.33±0.04b	0.12±0.02c	***
Large tree	0.62±0.02a	0.30±0.03b		***
Overall tree	0.67±0.03a	0.38±0.02b	0.28±0.01c	***

Notes: a, identical letters within a row indicate that means were similar ($P < 0.05$, Tukey test); $n = 6$ for all means of saplings 2.0–9.9 cm DBH, poles 10.0–29.9 cm DBH, large trees ≥ 30.0 cm DBH and overall trees ≥ 2.0 cm DBH; $n = 24$ for mean of seedlings < 2.0 cm DBH, ≥ 50.0 cm tall. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

and it is more favor to sustainable timber output (Nolet *et al*., 2014).

4.2 Effects of logging intensity on species composition

Some researchers found relatively little impact of harvesting on species composition (Hall *et al*., 2003; Angers *et al*., 2005), while others demonstrated the opposite results (Parrotta *et al*., 2002; Ramovs and Roberts, 2003). The difference might result from different logging intensities. In this study, forest treatments of T_0 and T_1 were dominated by six tree species, *P. koraiensis*, *T. amurensis*, *Q. mongolica*, *F. mandshurica*, *A. pseudo-sieboldianum* and *A. mono*. These species comprised 93% and 85% of the total basal area in T_0 and T_1, respectively (Table 2). These percentages of dominant trees mirror the typical composition of the climax stage of the BKF (Su *et al*., 2010). Conversely, these six species dominant in primary BKF only comprised 45% of the total basal area in T_2 and about 10% in T_3. Moreover, the values of the three indices (C_J, C_{MH} and C_N), which are usually used to represent community similarity (Ma *et al*., 1995), were the highest for T_0 and T_1, followed by T_0 and T_2, and T_0 and T_3, in generally (Table 3). The results suggest that shifts in species composition are related to logging intensity, impacts of harvesting on tree species composition increase with logging intensity increasing. The reason might be that, low-intensity harvesting preserves primary habitat while maintaining more dominate trees in primary BKF. In this process, merely existing stems in the understory, especially more shade tolerant species such as *A. pseudo-sieboldianum* are released from suppression (Hart and Mayer, 2009). In contrary, the moderate intensity harvesting decreases the number of dominate trees, dramatically altering the environment of the forest floor, and leading to pioneer species (e.g., *P. davidiana* and *S. matsudana*) colonizing the site (González-Alday *et al*., 2009). Clear-cutting removes all original vegetation, and thereafter pioneer species invade and dominate the site (Chen *et al*., 2003).

Compared to the treatments of T_2 and T_3, low intensity harvesting treatment T_0 maintains superiority of dominate tree species in primary BKF, and preserves original habitat. This is a key precondition for keeping the ecosystem stable (Hall *et al*., 2003). In addition, the six tree species (*P. koraiensis*, *T. amurensis*, *Q. mongo-

lica, *F. mandshurica*, *A. pseudo-sieboldianum* and *A. mono*), which are dominant in primary BKF, are also yield timber of high economic value (Dai *et al*., 2004). Low intensity harvesting treatment is more beneficial to keep sustainable output of high quality timbers, while remaining more of these more valuable trees. Although pioneer species (*P. davidiana* and *B. platyphylla*), which accounted for large proportions of T_2 and T_3, grew rapidly (Table 2), it is unlikely that such rapid growth trends would be maintained due to their short life period (Hall *et al*., 2003; Zhang *et al*., 2013). Moreover, these pioneer species are of low economic value.

Ideally, harvesting treatments should be investigated after the same years of recovery. In this study, intervals between harvests and plot investigation were 9 years, 21 years and 29 years for T_1, T_2 and T_3, respectively. It should be noticed that, although recovery time for T_1 was the shortest, the composition and structure of T_1 were the most closely to T_0 among the three treatments. This further reflected the fact that low intensity harvesting treatment is more conductive to maintaining forest structure and composition. Moreover, this study is not a controlled experiment, and it is hardly to get replicate stands in field conditions. Although we established more replicate plots in each treatment, and divided them in relatively long distances, this study remained some uncertainties.

5 Conclusions

In generally, the effects of harvesting on forest structure and tree species composition varied with different logging intensities. Low intensity harvesting had little impact on either of these two characteristics, providing evidence that forests logged at low intensity would recover pre-harvest structure and composition in a short time period. Moderate intensity harvesting significantly altered forest structure and tree species composition, and it indicated that its effects would last for decades. Clear-cutting removed all vegetation, and several centuries would be required for the forest to recover the composition and structure of a primary forest. In light of the above, low intensity harvesting combined with short rotations would be most conducive to maintaining forest ecosystem stability while concurrently ensuring the sustainable production of high quality timber. These results suggest that a harvesting model with low intensity and short rotation is a sustainable harvesting method for BKF on the Changbai Mountains.

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