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Feasibility of implementing thinning in even-aged *Larix olgensis* plantations to develop uneven-aged larch–broadleaved mixed forests

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Abstract Thinning experiments were conducted in larch (*Larix olgensis*) plantations to assess the feasibility of converting even-aged plantation stands to uneven-aged forests with more complex stand structures. Stands established in 1965 and 1960 were thinned in 2004 (Regime A, for determining the effect of recent thinning on emergence of seedlings) and 1994 (Regime B, for examining the effects of the past thinning on establishments of recruitments), respectively, at two intensities each. Natural regeneration, together with litter depth, canopy openness and vegetation cover, was surveyed in the thinned plots. Results indicated that larch seedlings started to emerge in May, reached a peak in June, decreased from June through September, and then disappeared in October. No larch seedlings exceeded 1 year old in the thinned plots because of the low levels of light and dense litter and vegetation cover. However, there were many naturally regenerated seedlings (5–50 cm in height) and saplings (50–500 cm in height) of broadleaved tree species such as *Acer* spp., *Fraxinus* spp., *Cornus controversa*, *Quercus mongolica*, and even the climax tree species, *Pinus koraiensis*, in the thinned plots. The mean density of regenerated seedlings reached 6.7 and 4.5 stems m^{-2} in Regimes A and B, respectively, whilst the mean density of regenerated saplings reached 4,595 stems ha^{-1} in Regime B. These results suggest that it is impractical to turn even-aged larch plantations to uneven-aged larch forests, but it may be feasible to develop uneven-aged larch-broadleaved forests from even-aged larch plantations through thinning.

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Introduction

Thinning is a tending procedure of selective removal of trees from a plantation to reduce competition and provide increased space into which the remaining trees can extend their canopies and grow faster (Thaiutsa et al. 1991). In addition to promoting the growth of planted trees, through reducing stem density, thinning can increase canopy openness (light availability), modify soil temperature and water conditions, affect the quantity and quality of litter, and eventually facilitate the natural regeneration of forests by forming gaps (Gray and Spies 1996; Mizunaga 2000; Sophie 2003; Zhu et al. 2003; Simard et al. 2004). Therefore, thinning is considered as an indispensable management approach for improving natural regeneration in forests (Meer et al. 1999; Marilou and Messier 2002; Laurent et al. 2003; Albrecht and McCarthy 2006; Iverson et al. 2008; Zald et al. 2008), and can play crucial role to sustainable development of forest ecosystems (Krauchi et al. 2000; Albrecht and McCarthy, 2006). In particular, thinning is important for converting pure plantations to uneven-aged stands and can promote the multiple ecological services that forests provide (Franklin et al. 1986; Zhu et al. 2003; Hanley et al. 2006).

In China, more than one-third of the national forests are distributed in Northeast China. The natural mixed broadleaved–Korean pine (*Pinus koraiensis* S. et Z) forest (MBKPF), one of the regional climax forests in Northeast China, is the largest and the most important forest type within the national forests for timber production and for providing other ecological services (Chen et al. 2003; Liu et al. 2005). However, more than 70% of the MBKPFs have become secondary forests due to a century of excessive timber harvesting by foreign and domestic forces; Korean pine trees have greatly decreased in number in the regional natural forests, or even disappeared in some areas (Chen et al. 2003; Zhu et al. 2007). In order to spur rapid economic development, *Larix* spp. (*L. olgensis* or *L. keampferi*) have been widely planted as commercial timber tree species in place of the secondary forests in recent decades (since the 1950s) in Northeast China. The most common practice involves planting larch seedlings on sites of some 3- to 20-ha clear cuts in the secondary forests (Wang and Liu 2001; Zhu et al. 2008). Currently, many of the secondary forests have been converted into larch plantations, which amount to some 2 million ha in Northeast China (Liu et al. 2005). Although playing an important role in timber production, larch plantations have been fraught with many potential problems. For example, it is difficult for planted larch stands to naturally regenerate (Wang and Zhang 1990; Ban and Xu 1995; An et al. 1997); larch plantations are vulnerable to disease and pest insects, and often lead to soil fertility decline (Liu et al. 1998; Xu et al. 2000; Li 2004). The replacement of natural mixed broadleaved–Korean pine forests by larch plantations also causes ecological and environmental problems such as loss and fragmentation of natural habitats and reduction of biodiversity, consequently leading to the debasement of ecological function (Hibbs and Bower 2001).

Because of a lack of natural regeneration capability, seedlings have to be replanted after harvesting the mature stands to maintain larch plantations. However, natural regeneration is viewed as an effective forest management strategy with low cost and high productivity (Wang et al. 2005), which is in accordance with modern sustainable management of forest resources and biodiversity protection (Dong 2001; Deal 2007). Tsuyuzaki (1994a, b) found that the growth and seedling establishment of *L. olgensis* were not affected by thinning intensities (light conditions) but by soil nutrient availability. Wang and Zhang (1990) suggested that *L. olgensis* could naturally regenerate in pure or mixed forests in Changbai Mountain (41°42′–42°25′N, 127°43′–128°17′E), especially after fire disturbances. There is also experimental evidence that forest floor conditions, including litter layer, root layer, grass cover and moss depth, are more important than the light conditions in affecting natural regeneration in larch stands (Ban and Xu 1995; An et al. 1997). Recently, there have been reports that *L. olgensis* plantations had the potential to spontaneously develop mixed forests (Wang and Liu 2001; Lü et al. 2008), especially in the clear cutting area; *L. olgensis* natural regeneration could be a possible means of artificial promotion (Wang and Zhang 1990; Lü et al. 2008). However, so far the promise of feasible natural regeneration of larch seedlings under larch plantations comes mostly from theoretical analysis, with a few based on experimental observations. Additionally, previous reports on the regeneration of *L. olgensis* plantations also exhibited quite different pictures as mentioned above.

This concern for ecological and environmental problems caused by larch plantations has led many researchers to focus on soil degradation. Liu et al. (1998) attributed the soil degradation of larch plantations to poor quality of larch litter, which is known to decompose very slowly. However, the problem of soil degradation can be overcome by thinning, as this significantly increases the soil organic carbon concentrations by regulating soil chemical properties (Hwang and Son 2006). Furthermore, the available nutrients can be improved by thinning through increasing the broadleaved tree species (Chen et al. 1998). Many studies demonstrated that thinning could turn the pure plantations to uneven-aged forests with more complex stand structures through natural regeneration (Wang and Zhang 1990; Gobbia and Schlichterb 1998; Liu et al. 2005; Albrecht and McCarthy 2006; Iverson et al. 2008). The complex structures could lead to high biodiversity and more forest canopy layers, which are beneficial to alleviating the fragmentation of natural habitats and to maintaining the ecological functions of forests (Deal 2007). However, information is lacking on the practice of implementing thinning in *L. olgensis* plantations to develop uneven-aged forests with more complex stand structures.

Faced with the problems of increasing plantations at the expenses of natural forests, a strategy of forest development under the framework of sustainable development, the Natural Forest Conservation Programme (NFCP), was set up by the central government of China in 1998 (Xu et al. 2000). One of the major objectives of NFCP is to restore the natural forests and maintain a multiple-use policy in plantation forests (Li 2004). Therefore, natural regeneration for plantation forests has been actively promoted in China as "nature-approximating forestry" (Franklin et al. 1986).

In order to promote the growth, several times of thinning should be conducted for the larch plantations. Generally, the initial thinning of *L. olgensis* plantations with 3,300–4,400 stems ha^{-1} was conducted around 15 years old

(Wang and Zhang 1990). After the first thinning, the necessity of later thinning is dependent on the growth status. However, little information about the effects of recent and past thinning on the establishment of regeneration is known for the *L. olgensis* plantations. Therefore, we conducted a study to test the feasibility of implementing thinning in larch plantations to develop uneven-aged larch/larch–broadleaved mixed forests with more complex stand structures through natural regeneration. Two thinning regimes (recent and past thinning) were employed in this study. One was used for assessing the effect of recent thinning on emergence and survival of naturally regenerating seedlings of larch and broadleaved tree species, whilst the other was used for examining the effect of the past thinning on the establishment of recruitments for broadleaved tree species.

Materials and methods

Study site

The study site was located at the Qingyuan Experimental Station of Forest Ecology (QESFE), Institute of Applied Ecology, Chinese Academy of Sciences, in a mountainous region in eastern Liaoning Province, Northeast China (41°51′N, 124°54′E, 500–1,100 m above sea level). The climate is of continental monsoon type, with a monsoon and windy spring, warm and humid summer, and dry and cold winter. The annual mean air temperature is 4.7°C, with a minimum monthly temperature of −12.1°C in January and a maximum monthly temperature of 21.0°C in July. Mean annual precipitation is 810.9 mm. The frost-free period is 130 days on average, with the first frost in October and the last in April. The soil type is a typical dark brown forest soil with a thickness of 30–60 cm (Zhu et al. 2008). Secondary forests formed about 55 years ago after destructive cutting and burning dominate the site. The composition of the secondary forests includes the major tree species such as *Acer* spp, *Quercus mongolica*, *Fraxinus mandshurica*, *F. rhynchophylla*, *Juglans mandshurica*, *Phellodendron amurense*, *Populus davidiana*, *Tilia* spp., *Ulmus* spp, *Alnus sibirica*, *Betula costata*, and *Cornus controversa* (Zhu et al. 2007). Larch plantations and Korean pine plantations accounted for 20% in the form of disjunct patches of varying sizes within the secondary forests.

Thinning treatments

Thinning treatments included two regimes: one was thinned in 2004 on 3.4 ha of *L. olgensis* stands planted in 1965 (Regime A; also referred to as recently thinned stands), and the other in 1994 on 3.1 ha of stands planted in 1960 (Regime B; also referred to as early thinning stands). These stands were located on gentle slopes (less than 15°), with southerly aspects. The two *L. olgensis* plantations were surrounded by mixed broadleaved secondary forests.

Regime A The stand was thinned by the local forestry farm in 1981 for improving tree growth. The latest thinning was conducted in 2004 with a random thinning pattern at two intensities, i.e., thinned to about 30% (Regime A1, three 20 m × 20 m plots) and 50% (Regime A2, two 20 m × 20 m plots) of the preserved stem density. The thinned stands had densities of 1,029 and 961 stems ha^{-1} and a basal area of 28.14 and 25.94 m^2 ha^{-1} for Regime A1 and Regime A2, respectively (Table 1).

Regime B With the same thinning pattern as in Regime A, the latest thinning was conducted in 1994 (previous to this thinning, another thinning was conducted by the local forestry farm in 1976) with about 40% (Regime B1, two 20 m × 20 m plots) and 60% (Regime B2, two 20 m × 20 m plots) of the preserved stem density. In 2005, the thinned stands had densities of 925 and 663 stems ha^{-1} and a basal area of 38.79 and 35.03 m^2 ha^{-1} for Regime B1 and Regime B2, respectively (Table 1).

Assessment of environmental conditions

Canopy openness was estimated in August 2005 using hemispherical photographs. The silhouettes of hemispherical photographs were taken at nine random points on each plot with a digital camera levelled 1.0 m above the forest floor on cloudy days or at dawn and dusk. A 180° fisheye lens (Nikon FC-E8, f = 8–24 mm) was mounted on a Nikon digital camera (Coolpix 910, f = 7–21 mm; Nikon, Japan) (Zhu et al. 2003). The hemispherical photographs were analyzed with the processes developed by ter Steege (1993) using the CanopOn Program (http://takenaka-akio.cool.ne.jp/etc./canopon2/).

Understory vegetation cover and litter depth were measured at random points on each thinned plot between June and August 2005. Understory vegetation cover was visually estimated at three heights (i.e., 0–10, 10–30, and >30 cm above the forest floor) with three reiterations on each plot for identifying the light conditions at different levels. Litter depth was measured at more than nine random points on each plot.

Regeneration sampling

Natural regeneration was sampled on treatment plots in 2004 and 2005 for Regime A (1 and 2 years after thinning) and in 2005 for Regime B (11 years after thinning).

In Regime A, the emergence of larch seedlings was monitored at weekly intervals from 15 April through 30 May

Table 1 Thinning treatments and stand characteristics

Plot	Stem density (trees ha^{-1})		Basal area (m^2 ha^{-1})		Mean DBH (cm, mean ± SE)		Mean height (m, mean ± SE)	
	Before thinning[a]	After thinning[b]	Before thinning[a]	After thinning[b]	Before thinning[a]	After thinning[b]	Before thinning[a]	After thinning[b]
Regime A1								
Plot 1	1,827	1,063	39.97	30.54	15.9 ± 5.2	18.6 ± 4.4	17.2 ± 3.7	17.8 ± 1.6
Plot 2	1,596	1,120	33.47	29.11	15.5 ± 5.1	17.6 ± 4.5	17.1 ± 3.6	17.6 ± 1.1
Plot 3	1,438	904	28.55	24.77	14.7 ± 6.0	17.9 ± 5.3	16.9 ± 4.3	17.7 ± 1.3
Mean	1,620	1,029	34.00	28.14	15.4	18.1	17.1	17.7
Regime A2								
Plot 4	1,980	976	43.46	26.87	15.8 ± 5.4	17.8 ± 4.9	17.2 ± 1.3	17.6 ± 1.2
Plot 5	1,860	947	40.20	25.01	15.7 ± 5.4	17.7 ± 5.0	17.1 ± 4.1	17.6 ± 1.2
Mean	1,920	961	41.83	25.94	15.8	17.7	17.2	17.6
Regime B1								
Plot 1	1,422	850	16.62	37.81	12.2 ± 5.0	23.8 ± 4.9		17.3 ± 1.7
Plot 2	1,603	1,000	17.83	39.76	11.9 ± 5.8	22.5 ± 2.1		18.3 ± 1.5
Mean	1,513	925	17.23	38.79	12.1	23.2		17.9
Regime B2								
Plot 3	1,558	650	19.12	34.78	12.5 ± 4.2	26.1 ± 4.5		19.8 ± 2.0
Plot 4	1,535	675	20.06	35.29	12.9 ± 5.0	25.8 ± 3.2		20.6 ± 1.5
Mean	1,546	663	19.59	35.03	12.7	26.0		20.5

[a] Before thinning means the data observed in 2004 for Regime A, in 1994 for Regime B. Data of mean height for Regime B were not recorded in 1994 because the thinning was conducted by the local forestry farm

[b] After thinning means the data observed in 2005, i.e., soon after thinning for Regime A, and 11 years after thinning for Regime B

in 2004 and 2005; while the survival of larch seedlings was monitored at monthly intervals between 30 May and 28 September in 2005 since 2004 was a mast year for larch seeds (see Liu et al. 2007). The emergence of larch seedlings was defined as the stage when the first aboveground primary needles became visible, and establishment was defined as survival throughout the study period (to October 2005), as suggested by Xiong and Nilsson (1999). Monitoring of larch seedlings was conducted in each 1 m × 1 m quadrat at an interval of 1 m along the diagonal lines of the plots (28 quadrats in each plot). The regenerated seedlings of broadleaved tree species and Korean pine (the disappeared dominant tree species during the formation of the secondary forest ecosystem) were investigated on each sample plot (each plot was divided into 100 sub-plots of 2 m × 2 m) between August and October of 2004 and 2005.

In Regime B, regeneration of broadleaved tree species and Korean pine was investigated in each sample plot with the same procedures as in Regime A between August and October of 2005. At each sub-plot, regenerated seedlings (height of seedling was more than 5 cm and less than 50 cm) or saplings (height of sapling was equal to or more than 50 cm and less than 500 cm) of all tree species were recorded. In addition, the height and base diameter of saplings were measured in each plot.

Statistical analyses

The importance value (IV) of regenerated saplings of species occurred was computed as $IV = (D + C + F)/3$ (D: the relative density, C: the relative cover, and F: the relative frequency) (Zhu et al. 2007). After presenting the means and standard errors for comparative information (Iverson et al. 2008), we conducted the one-way ANOVA, and with repeated measures when necessary, to distinguish the differences within each sample plot. Differences identified at a level of $p < 0.05$ were considered significant. The relationship between variables related to regeneration and canopy openness was tested using Bivariate Correlations (Spearman). All the analyses were conducted in a SPSS package (Version 13.0).

Results

Canopy openness, litter depth and understory vegetation cover

Canopy openness exhibited distinct differences between plots of Regimes A1 (23.5%) and A2 (34.0%), but was similar between Regimes B1 (14.2%) and B2 (16.8%) (Fig. 1A).

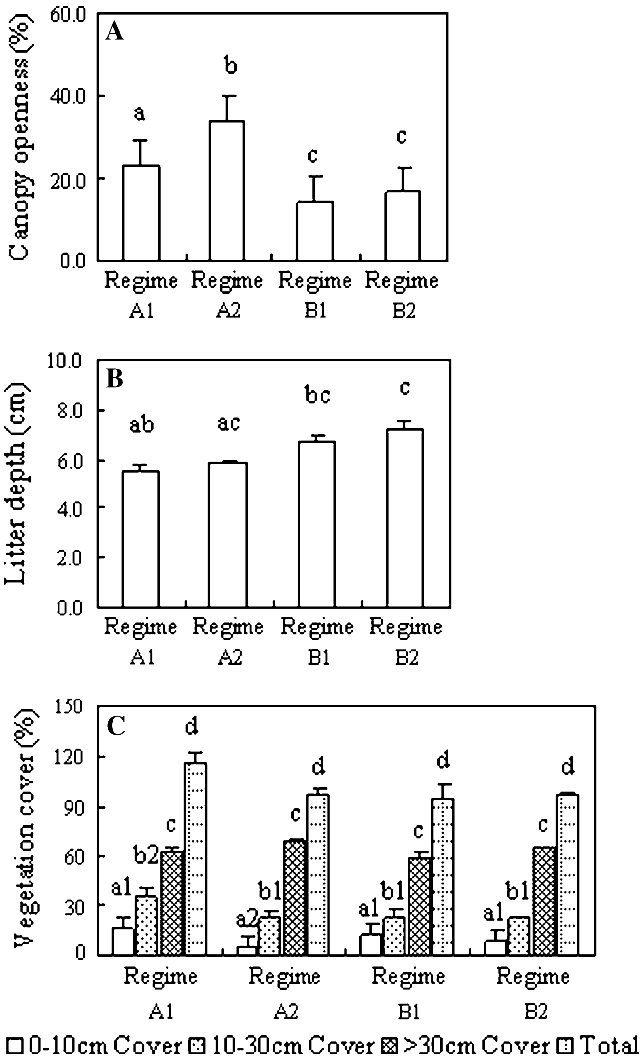

Fig. 1 Characteristics of environmental factors in the thinned stands. **A** Canopy openness; **B** litter depth; **C** vegetation cover. *Vertical bars* are standard errors. *Different letters above the error bars* indicate significant differences between Regimes and layers ($p < 0.05$)

The litter depth varied between 5.6 and 7.2 cm in the plots. There were no significant differences between Regimes A1 and A2 and between Regimes B1 and B2; whilst a significant difference was found between Regimes A1 and B2 (Fig. 1B). The litter was composed mainly of intact *L. olgensis* tissues and other plant materials.

The percentage of understory vegetation cover was almost the same during the survey months (June, July and August) in the experimental stands. There was no significant difference in total understory vegetation cover between Regime A and Regime B (total vegetation cover varied between 95 and 116%). But significant differences were observed between sub-layers, e.g., in 0–10 cm layer, A2 was significantly lower than that of A1, B1 and B2; in the 10–30 cm layer, A1 was significantly higher than that of A2, B1 and B2 (Fig. 1C).

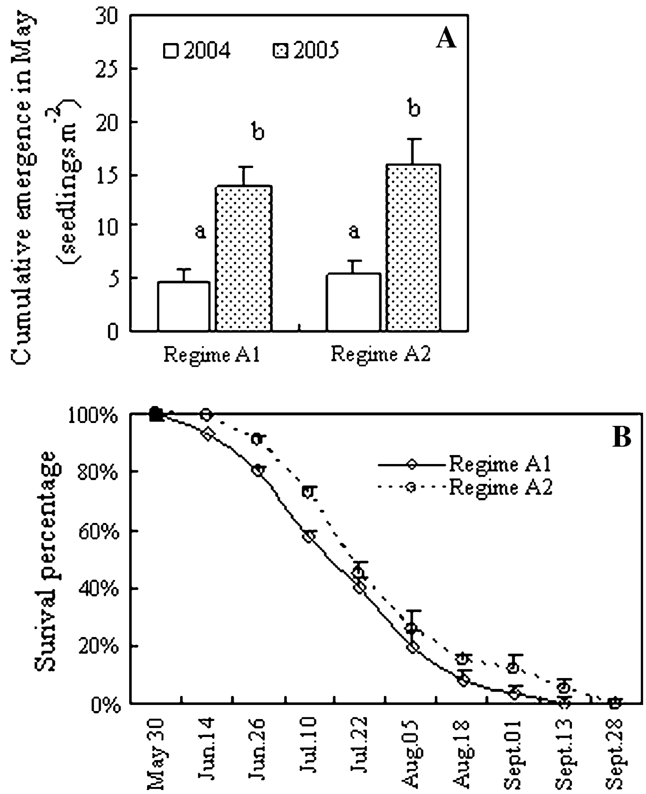

Fig. 2 Emergence and survival of *L. olgensis* seedlings in Regime A treatments. **A** Cumulative emergence of *L. olgensis* seedlings in May 2004 and 2005; **B** mean survival rate of *L. olgensis* seedlings over the monitoring period. *Vertical bars* are standard errors. *Different letters above the error bars* indicate significant differences between different thinning intensities and between 2004 and 2005 ($p < 0.05$)

Emergence and survival of *L. olgensis* seedlings

The seedlings of *L. olgensis* started to emerge around mid-May. The number of emerged seedlings did not significantly differ between Regimes A1 and A2 at the end of May in both 2004 and 2005 ($p = 0.846$, 0.352 for 2004 and 2005, respectively) (Fig. 2A). However, a significant difference was found between 2004 and 2005 due to differences in seed production between the two years (i.e., 2004 was a mast year, but 2003 was a lean year) (see Liu et al. 2007).

More than 80% of the seedlings died before the end of August; almost all seedlings in Regime A disappeared by mid-September (Fig. 2B), i.e., there were no seedlings over 1 year old in the experimental stands.

Emergence of broadleaved and pine tree species in recently thinned stands

The emerged seedlings were recorded for around 15 broadleaved species (totally 18 tree species were found, including one conifer species, *P. koraiensis*) in the recently thinned stands (Regime A), regardless of thinning intensities (Fig. 3A). The differences of emerged seedling

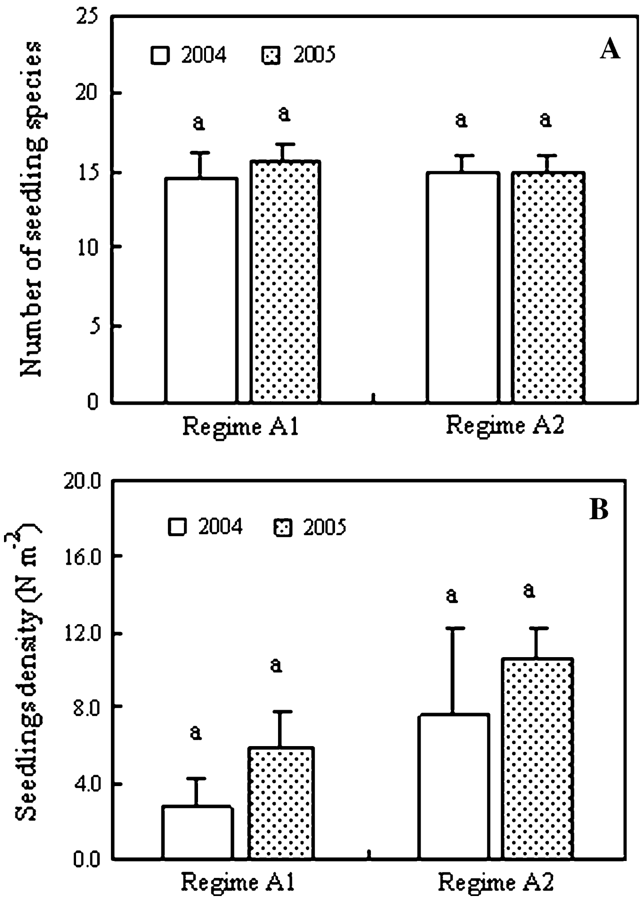

Fig. 3 Emergence of broadleaved tree species and pine in Regime A with two different thinning intensities. **A** Number of regenerated seedling species; **B** regenerated seedling density. *Vertical bars* are standard errors. *Different letters above the error bars* indicate significant differences between Regimes and between 2004 and 2005 ($p < 0.05$)

densities between thinning intensities (Regimes A1 and A2) and between 2004 and 2005 were not significant (Fig. 3B) ($p > 0.05$). The most abundant individual species was *F. rhynchophylla*, followed by *A. mono* in 2004 for both Regimes A1 and A2. However, the most abundant individual species changed in 2005 for Regime A1; *Phellodendron amurense* dominated the emerged seedlings, followed by *F. rhynchophylla*, *Cornus controversa* and *A. mono* (Table 2). The regenerated seedling density in Regime A2 was much higher than that in Regime A1 in both 2004 (2.67 times) and 2005 (1.82 times).

About 80% of the tree species on the forest floor increased in the number of regenerated seedlings from 2004 to 2005, but the opposite occurred for *Acer* spp. and *F. mandshurica* in Regime A1, and for *A. ukurunduense* and *Populus davidiana* in Regime A2 (Table 2). Overall, the emergence of the broadleaved tree species was relatively high right after thinning. The regenerated seedling density ranged from 2.83 to 10.60 seedlings m^{-2}, and averaged 4.73 and 7.73 seedlings m^{-2} for 2004 and 2005, respectively. In addition, seedlings of the climax tree species, *P. koraiensis*, appeared in both Regimes A1 and A2.

Establishment of broadleaved tree species in early thinning stands

The number of regenerated tree species was similar between plots of two different thinning intensities with around 10 species in both Regimes B1 and B2 (Fig. 4A, C). The regenerated seedling density ranged from 1.39 to 7.56 seedlings m^{-2}, and the regenerated sapling density ranged from 0.25 to 0.73 saplings m^{-2}. Significant differences were found in both seedling and sapling densities between Regimes B1 and B2 ($p < 0.05$) (Fig. 4B, D).

The regenerated seedling species and sapling species were consistent in Regimes B1 and B2, which consisted of *A. mono*, *A. pseudo-sieboldianum*, *F. mandshurica*, *F. rhynchophylla* and *Q. mongolica* etc. (Table 2). In both Regimes B1 and B2, the most abundant individual seedling species was *F. rhynchophylla*. The most abundant individual sapling species was *A. mono*, followed by *F. rhynchophylla* (Table 2). Thinning intensities seemed not to influence the species composition. However, the mean regenerated sapling density in Regime B2 was much higher (2.37 times) than that in Regime B1. In contrast, the regenerated seedling density was much higher (4.90 times) in Regime B1 than that in Regime B2 (Table 2).

Based on the importance values of saplings, the rank of regenerated sapling species in Regime B1 was in the order of *A. mono*, *F. rhynchophylla*, *C. controversa*, *Q. mongolica*, *A. pseudo-sieboldianum*, and *Sophora japonica*; the six species accounted for 89% of the regenerated saplings. In Regime B2, the rank was in the order of *A. mono*, *F. rhynchophylla*, *A. pseudo-sieboldianum*, *A. triflorum*, *F. mandshurica*, and *U. laciniata*; the six species accounted for 87% of the regenerated saplings. The natural regeneration of broadleaved tree species was high with the sapling density ranging from 2,536 to 7,256 saplings ha^{-1}. The densities of the two most common regenerated sapling species (*A. mono* and *F. rhynchophylla*) reached 861 and 2,971 saplings ha^{-1}, and 587 and 1,136 saplings ha^{-1} in Regimes B1 and B2, respectively.

Overall, both the mean basal diameter and mean height of saplings in Regime B2 were higher than those in Regime B1 (Fig. 5). However, patterns were inconsistent at species level; specifically, the basal diameter of *A. pseudo-sieboldianum*, *F. rhynchophylla* and *Q. mongolica* (Fig. 5A) and the height of *F. mandshurica*, *F. rhynchophylla* and *Q. mongolica* (Fig. 5B) were higher in Regime B1 than in Regime B2. *Q. mongolica* in Regime B1 and *U. laciniata* in Regime B2 had the highest basal diameters, and *U. laciniata* in Regime B2 had the highest height.

Table 2 Regenerated densities (seedlings or saplings m^{-2}) of broadleaved tree species and pine in Regime A and Regime B

Tree species	Regime A1		Regime A2		Regime B1			Regime B2		
	2004	2005	2004	2005	Sapling	Seedling	IV	Sapling	Seedling	IV
Acer mono	0.560	0.510	1.033	1.433	0.086	0.101	0.29	0.270	0.241	0.35
A. pseudo-sieboldianum	0.200	0.138	0.085	0.128	0.017	0.007	0.06	0.045	0.034	0.09
A. tegmentosum	0.065	0.050	0.055	0.070						
A. triflorum								0.055	0.020	0.09
A. ukurunduense			0.035	0.033				0.007		0.01
Alnus sibirica	0.058	0.058	0.053	0.053	0.008	0.016	0.03			
Betula costata	0.003	0.455	0.033	0.190						
Cornus controversa	0.165	0.760	0.048	0.478	0.040	0.115	0.15	0.007		0.02
Fraxinus mandshurica	0.098	0.093	0.075	0.123	0.007	0.098	0.03	0.060	0.044	0.09
F. rhynchophylla	0.640	1.133	5.395	5.580	0.059	6.963	0.23	0.112	1.117	0.16
Juglans mandshurica	0.083	0.143	0.108	0.215					0.004	
Phellodendron amurense	0.355	1.425	0.568	3.335						
Pinus koraiensis	0.098	0.125	0.033	0.033					0.004	
Populus davidiana	0.003	0.090	0.075	0.020						
Quercus mongolica	0.210	0.253	0.238	0.433	0.025	0.067	0.11	0.034	0.017	0.05
Sophora japonica	0.090	0.098	0.090	0.090	0.014	0.009	0.05	0.007	0.009	0.02
Sorbus pohuashanensis	0.033	0.033	0.015	0.028	0.009	0.018	0.03			
Tilia amurensis	0.043	0.048	0.020	0.040						
Ulmus laciniata					0.017	0.029	0.02	0.048	0.026	0.09
U. macrocarpa								0.020	0.000	0.03
U. pumila	0.198	0.508	0.013	0.115						
Sum	2.835	5.818	7.570	10.603	0.272	7.402	1.00	0.647	1.508	1.00

IV importance values of saplings

Relationships between canopy openness and regeneration status

The emerged seedling density in the recently thinned stands increased with canopy openness (Table 2). In addition, in the early thinning stands, sapling density and the size of both basal diameter and sapling height increased with increasing canopy openness (Table 2; Fig. 5). The densities of the six dominant individual sapling species (with the exception of *C. controversa*) also increased with increasing canopy openness (Table 2). However, the seedling density in the early thinning stands decreased with increasing canopy openness (Fig. 4B).

Discussion

Regeneration failure of *L. olgensis* in the thinned larch plantations

In this study, we found that seed sources and seed germination did not appear to limit the natural regeneration of *L. olgensis* since enough seeds germinated even in the lean year (about 5 emerged seedlings m^{-2}) (Fig. 2A). Also, light level seemed not to affect the seedling emergence since there was no significant difference between thinning intensities, in disagreement with some findings by others (Stoehr 2000; Zhu et al. 2003). This result may be related to the specific characteristics of *L. olgensis* (Tsuyuzaki 1994b). The emerged *L. olgensis* seedlings all disappeared at the end of September. This seemed to be because the understory vegetation cover, which by making the total cover exceed 95% influenced the light levels under the stands, i.e., seedling survival was strongly inhibited by shading of the understory vegetation in different layers (Fig. 1C), or by competition from surrounding plants (An et al. 1997). This observation is in accordance with the general relationships between seedling survival and light availability previously reported for shade-intolerant tree species (Chen and Klinka, 1998; Zhu et al. 2003). During the survey of seedling survival, we found that litter depth impeded the seedling roots from reaching the soil (data not shown). Therefore, although there were enough *L. olgensis* seedlings emerging in the thinned stands regardless of thinning intensities, no seedlings could survive to pass their first growing season (Fig. 2B). This suggests that the

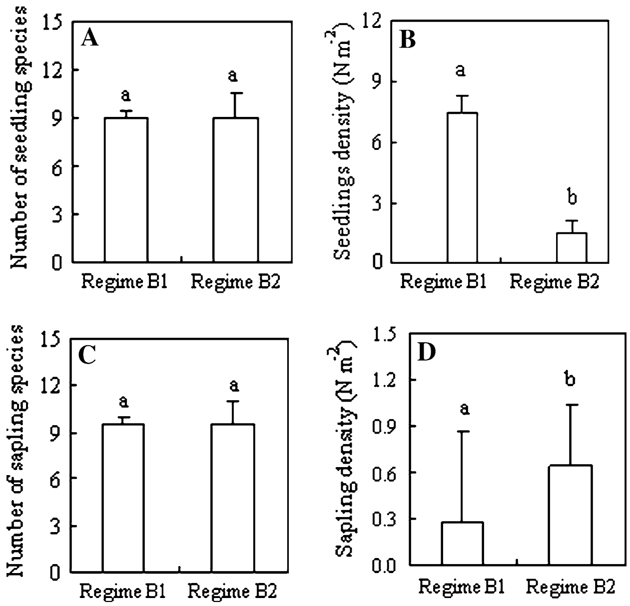

Fig. 4 Establishment of broadleaved tree species in Regime B with two different thinning intensities. **A** Number of regenerated seedling species; **B** regenerated seedling density; **C** number of regenerated saplings; **D** regenerated sapling density. *Vertical bars* are standard errors. *Different letters above the error bars* indicate significant differences between Regimes ($p < 0.05$)

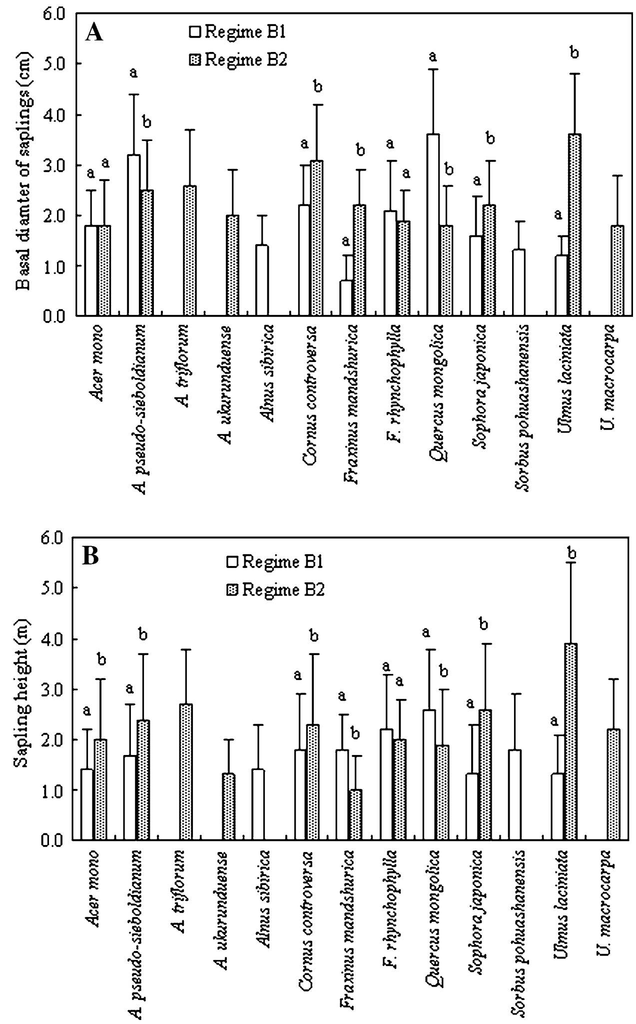

Fig. 5 Size of the saplings in past thinned stands in 2005. **A** Base diameter of saplings; **B** height of saplings. *Vertical bars* are standard errors. *Different letters above the error bars* indicate significant differences between Regimes A and B (different thinning intensities) ($p < 0.05$)

seedling establishment of *L. olgensis* in plantations is somewhat difficult. These results were consistent with other studies that reported poor natural regeneration of *L. olgensis* (Wang and Zhang 1990; Tsuyuzaki 1994a, b; Okitsu et al. 1995; Liu 1997; Zhu et al. 2008).

Establishment success of broadleaved tree species in the thinned larch plantations

The results of natural regeneration of broadleaved tree species indicated that the establishment of some broadleaved tree species was accomplished in both the recently thinned and early thinning larch plantation stands. Obviously, establishment means that seed sources, seed germination, emergence and survival should not be obstacles for the natural regeneration of some broadleaved tree species in the thinned larch plantations.

The 15 regenerated seedling species that appeared in the recently thinned plots are the dominant tree species in the secondary forests surrounding the larch plantations. The number of regenerated seedling species was similar under different thinning intensities, implying that the composition of the seed banks of the regenerated seedling species in the larch plantations was similar among treatment plots. These results are further confirmed by examining the regenerated sapling species in the early thinning stands (Regime B) (Table 2). The differences of regenerated seedling densities were not significant between plots of the two thinning intensities in Regime A (Fig. 3B), suggesting that the emergence of regenerated seedlings was not the problem impeding the natural regeneration of the broadleaved tree species. The most abundant species were similar in the first and second year after thinning at both thinning intensities (Table 2) (*F. rhynchophylla*, *A. mono*, *P. amurense*), indicating that dispersed seeds or the seed bank of the three tree species were abundant in the experimental site, which could be verified by examining the surrounding parent trees in the secondary forests (Hu et al. 2005).

Survival of seedlings or saplings is the necessary stage for successful natural regeneration. Around 10 regenerated sapling species and seedling species were found in the early thinning stands regardless of thinning intensities (Fig. 4A, C), of which more than 90% were identical to the species that emerged in the recently thinned stands (Table 2). Fewer regenerated tree species in the early thinning stands than in the recently thinned stands indicated that some regenerated seedling species could not survive after emergence because the more closed canopy induced unfavorable conditions for seedling survival. For example, both seedlings and saplings of *B. costata*, *Phellodendron amurense*, *Populus davidiana* and *Tilia amurensis* did not appear in the early thinning stands with more closed canopy (Fig. 1A) because these tree species are strong light-demanding species (Cao and Li 2003). In Regime A, the rank of the first two abundant seedling species was *F. rhynchophylla* > *A. mono*, but the rank of the first two abundant sapling species in Regime B was in reverse, i.e., *A. mono* > *F. rhynchophylla*. This reversion is in accordance with the properties of the two tree species—*A. mono* is more shade tolerant than *F. rhynchophylla* (Ren 1997).

The regenerated sapling density in more intensely thinned stands was two times more than that in less intensely thinned stands (Fig. 4D), supporting the conclusion that canopy openness plays an important role in the survival and establishment of the broadleaved tree species. That the densities of the three most abundant species of regenerated saplings (*A. mono*, *F. rhynchophylla* and *Q. mongolica*) increased with increasing canopy openness suggests that thinning increases canopy openness and provides more favored conditions for the survival and growth of sapling species. Furthermore, the three tree species have a certain degree of shade tolerance during early establishment (Cao and Li 2003). Particularly, *A. mono* has some degree of shade tolerance even for the big trees (Ren 1997). These may be the major reasons why the three tree species could naturally regenerate abundantly in the thinned larch plantations. Besides the most abundant species, other tree species such as *A. pseudo-sieboldianum*, *F. mandshurica* and *Cornus controversa* were also the main components of the regenerated sapling layer because of their shade tolerance capabilities (Table 2). The regenerated seedling density exhibited decreasing tendency with increasing canopy openness (Fig. 4B). This is because the light reaching the forest floor become worse due to interception by understory vegetations, i.e., the understory vegetations developed better when the canopy openness increased.

Possibility of natural regeneration for broadleaved tree species

There were sufficient regenerated seedlings and saplings of broadleaved tree species in the experimentally thinned plots. The regenerated seedlings appeared soon after thinning, and the seedling density were not significantly affected by the thinning intensities. The regenerated saplings in the early thinning stands formed the regeneration layer with an average height of 2.0 m and basal diameter of 2.1 cm (Fig. 5). Although the lack of temporal series of observations and the restriction of no control plots in our study, our results are similar to findings of Deal (2007) who found that a historical partial cutting without a planned silvicultural system ensured spruce regeneration, stand growth, or the maintenance of complex stand structures found in old-growth forests in southeast Alaska. Some of the environmental factors such as soil water, temperature and photosynthetically active radiation were not measured in our study; instead, we used canopy openness as an integrative indicator of understory environment (Zhu et al. 2008). Overall, the following conclusions could be drawn from this study: (1) thinning alone fails to turn even-aged larch plantations to uneven-aged larch forests since the *L. olgensis* seedlings could not survive without favored regeneration conditions; (2) it is likely that thinning will lead to the formation of uneven-aged mixed larch–broadleaved forests since both the establishment of regenerated seedlings and saplings succeeded in the recently thinned and early thinning stands. There are three reasons to support the second conclusion: firstly, there are enough seeds of broadleaved species coming from the secondary forests surrounding the larch plantations; secondly, canopy openness in the thinned stands can provide the necessary light conditions for seedling survival and sapling growth; and thirdly, most of the regenerated broadleaved tree species have some degree of shade tolerance during early establishment.

Additionally, the seedlings of the vanished dominant climax tree species, Korea pine (*P. koraiensis*), appeared in the thinned larch stands as there are scattered Korea pine trees in the secondary forests. Seeds of Korea pine could be brought in by feeding animals to the thinned plots. Therefore, it may be a chance to develop the current larch–broadleaved stands into MBKPF if the Korea pine seedlings can be conserved.

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