Forest recovery after clear-cutting in Chinese pine (Pinus tabuliformis) plantations of North China postprint

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Abstract

In Hebei Province of North China, forest was recovered with natural recruitment in plantations with large area of clear-cutting Chinese pine (Pinus tabuliformis). This study was aimed to demonstrate the dynamic characteristics of recruits during the natural recruitment. Both plot survey and the spatial point-pattern analysis were performed. Five developmental stages of natural recruitment were selected and studied, including 1 year before and 2, 5, 8, and 11 years after clear-cutting. Different slope aspects were also included. Natural recruitment was always dominated by Chinese pine with a proportion of higher than 90%. For plots of 1 year before clear-cutting on east- and north-facing slopes, recruit densities were 7886 and 5036 stems/hm2, the average heights were 0.78 (±0.85) and 1.06 (±1.15) m, and the average diameters at breast height (DBH) were 3.21 (±1.38) and 2.91 (±1.38) cm
cutting, recruit density was initially increased, then it was gradually declined with time; however, the variation of
cutting. The average height of recruits continued to increase after clear-cutting. For the plots of 11 years after clear-cutting on east- and north-facing slopes, average heights of recruits reached 2.00 (±1.14) and 2.24 (±1.20) m, respectively. The statuses of recruits on north-facing slopes were better than those on east-facing slopes after clear-cutting. Meanwhile, recruits on east-facing slopes were always aggregated at small scales, while spatial pattern of recruits varied with time on north-facing slopes. Moreover, forest was recovered more quickly by natural recruitment than by artificial afforestation after clear-cutting. The structural diversity was higher in naturally regenerated forests than in plantations of the same age. Our results demonstrated that clear-cutting of Chinese pine plantations recovered by natural recruitment has the potential to be an effective approach for establishing multifunctional forest.

Full Text

Preamble

Forest Recovery After Clear-Cutting in Chinese Pine (*Pinus tabuliformis*) Plantations of North China

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Abstract

In Hebei Province of North China, forest recovery through natural recruitment has occurred in large areas of clear-cut Chinese pine (*Pinus tabuliformis*) plantations. This study aimed to characterize the dynamic patterns of recruits during natural regeneration, employing both plot surveys and spatial point-pattern analysis. Five developmental stages of natural recruitment were examined: one year before clear-cutting and two, five, eight, and eleven years after clear-cutting, with different slope aspects also considered. Natural recruitment was consistently dominated by Chinese pine, accounting for over 90% of individuals. In plots one year before clear-cutting, recruit densities were 7,886 and 5,036 stems/hm^2 on east- and north-facing slopes, respectively, with average heights of 0.78 ($±0.85) m and 1.06 (±1.15) m, and average diameters at breast height (DBH) of 3.21 (±1.38) cm and 2.91 (±1.38) cm.
cutting, recruit density initially increased then gradually declined over time, whereas average DBH showed the opp
clear − cutting. Average recruit height continued to increase after clear − cutting, reaching 2.00 (±1.14) m and 2.24 (±$1.20) m in east- and north-facing plots eleven years after clear-cutting, respectively. Recruits on north-facing slopes exhibited better condition than those on east-facing slopes post-clear-cutting. Spatially, recruits on east-facing slopes remained aggregated at small scales, while spatial patterns on north-facing slopes varied temporally. Moreover, forest recovery via natural recruitment proceeded more rapidly than through artificial afforestation after clear-cutting, with naturally regenerated forests displaying higher structural diversity than plantations of the same age. Our results demonstrate that clear-cutting of Chinese pine plantations with natural recruitment recovery has strong potential as an effective approach for establishing multifunctional forests.

Keywords: Chinese pine; natural recruitment; clear-cutting; slope aspect; spa-

tial pattern; Hebei Province

1 Introduction

Chinese pine (*Pinus tabuliformis*) constitutes an important vegetation species in North China [?]. Since the 1950s, the government has established numerous Chinese pine plantations across North China for timber production, resulting in extensive plantation coverage. Given that the typical felling age for Chinese pine plantations is 50 years, many stands have now reached the final harvesting stage, with clear-cutting being the standard management practice. Forest managers increasingly expect forest reconstruction through natural recruitment due to its multiple advantages, including higher recruit density [?], greater structural diversity [?], better conservation of local vegetation genotypes [?], and reduced management costs [?].

Numerous studies have confirmed that forests can successfully regenerate after clear-cutting, with naturally recruited stands in temperate conifer plantations closely resembling natural forests [?, ?, ?, ?]. Consequently, further investigation of natural recruitment processes can help predict successional trajectories and optimize management strategies [?, ?]. By 2015, the earliest clear-cut Chinese pine plantations in North China had been recovering for 11 years, yet to our knowledge, no studies have documented the recruitment dynamics of Chinese pine during this period.

Current research on post-clear-cutting recruitment has primarily focused on species composition [?, ?, ?], vertical structure of recruits [?, ?, ?], and recruitment characteristics including density [?, ?, ?], growth status [?, ?], and age [?, ?, ?]. Additionally, researchers have found that natural recruitment dynamics relate to spatial patterns of vegetation across different height and age classes [?, ?, ?, ?]. While these aspects are all relevant, our study emphasizes two critical factors for further investigation. First, advanced regeneration has proven essential to post-clear-cutting forest restoration [?, ?, ?], with older advanced recruits serving as important seed sources for further forest reconstruction [?]. Therefore, we examined advanced regeneration one year before clear-cutting to reveal its growth conditions, explore clear-cutting effects, and identify relationships between advanced regeneration and forest recovery. Second, slope aspect significantly influences natural recruitment in Chinese pine plantations [?, ?, ?, ?], prompting analysis of slope aspect effects on recruitment characteristics. Accordingly, our study objectives were: (1) to elucidate advanced regeneration dynamics and its role in forest recovery after clear-cutting; (2) to identify temporal variation trends in natural recruitment following clear-cutting; and (3) to assess slope aspect effects on natural recruitment.

2.1 Study Area

The study area comprised Chinese pine plantations located in Pingquan County, Hebei Province, North China (Fig. 1

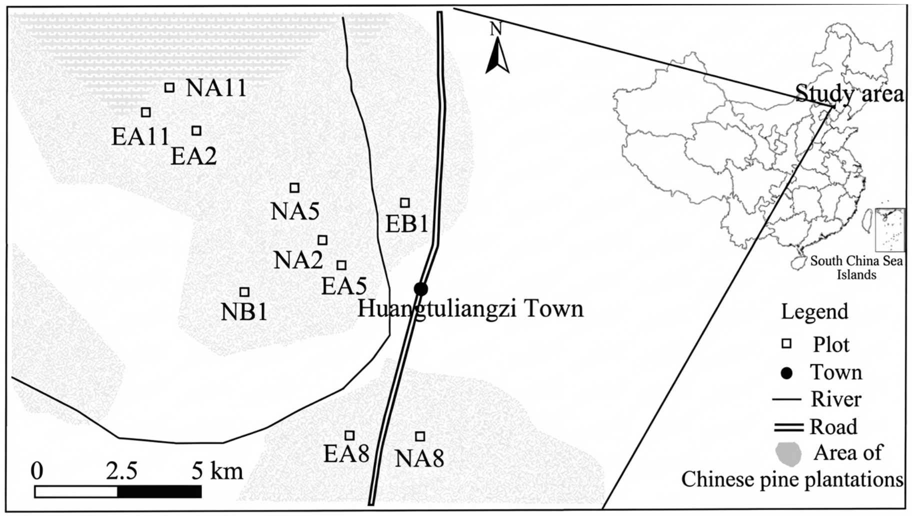

Figure 1: Figure 1

), approximately 250 km northeast of Beijing. The region experiences a temperate continental monsoon mountain climate, with an annual mean temperature of 7.4°C and annual precipitation ranging from 356.7–620.3 mm between 2004 and 2015 (Table 1). The predominant soil type is mountain cinnamon soil with gravel. In this area, plantations account for 95% of the total forest area in Pingquan County, with four main species: Chinese pine, aspen (*Populus davidiana*), Mongolian oak (*Quercus mongolica*), and black locust (*Robinia pseudoacacia*). Chinese pine plantations cover the largest area at 8,901.85 hm^2, representing 61.6% of the local total forest area.

2.2 Data Collection

Sampling was conducted along a chronosequence, with ten forest stands selected across different developmental stages and slope aspects. Two slope aspects were examined: east and north (n=5 each). Chinese pine plantations in this region are primarily distributed on half-shady (east- and northwest-facing) and shady (north- and northeast-facing) slopes due to precipitation limitations (Table 1). Thus, east- and north-facing slopes were selected to represent half-shady and shady conditions, respectively. Five stands on east-facing slopes were sampled from plantations one year before clear-cutting and two, five, eight, and eleven years after clear-cutting, designated as EB1, EA2, EA5, EA8, and EA11. Similarly, five stands on north-facing slopes were sampled at the same intervals, designated as NB1, NA2, NA5, NA8, and NA11. Stand characteristics are presented in Table 2 . Chinese pine was the sole canopy tree species in all plantations, with only one canopy layer. Stands EB1 and NB1 were 49-year-old Chinese pine plantations; since the general cutting age is 50 years, these stands represented conditions one year before clear-cutting.

This sampling design aimed to characterize advanced regeneration status before clear-cutting and demonstrate clear-cutting effects on advanced regeneration. For plantations two, five, eight, and eleven years after clear-cutting, all canopy trees were removed via clear-cutting, with no artificial afforestation conducted afterward. Forest recovery depended entirely on natural recruitment.

Because vegetation growth characteristics span multiple years and are difficult to track continuously, most studies exploring long-term variations compare growth characteristics across different developmental stages [?, ?, ?]. Field sampling and investigation were conducted from June to September 2015. Selected plots (60 m $\times$ 60 m) were located in the center of each stand, with plot boundaries at least 50 m from stand edges or cutting blanks. One plot was sampled per stand, named according to its corresponding stand. For each plot, species, quantity, height, and coordinates were recorded for all recruits (height \$ \$0.1 m), and DBH was measured for recruits (height \$ \$2 m). Canopy tree coordinates were also recorded in EB1 and NB1 plots. Additionally, ten 5 m $\times$ 5 m quadrats were randomly established in each plot to record recruit age. Recruits were classified as seedlings (0.1 m $<$ h $\leq$ 0.5 m) or saplings (h $>$ 0.5 m), with only established recruitment (seedlings surviving at least two years) considered [?]. Most observed recruits were Chinese pine, which exhibits high mortality in the first two years [?]. Recruit age was determined through tree-ring analysis of increment cores or basal sections using WinDENDRO™ (2005).

2.3.1 ANOVA Test

One-way ANOVA was applied to analyze differences in recruit height, DBH, and age among plots with different slope aspects or developmental stages. Data analysis followed a randomized complete block design, with normality and equal variance checked and an unequal variance model applied when necessary.

2.3.2 Spatial Point Pattern Analysis

Ripley’ s K function incorporates all information within a certain radius (scale), but as radius increases, small-distance information becomes confounded with large-scale results due to cumulative calculation effects [?, ?, ?]. Moloney’ s O-ring statistics, based on Ripley’ s K function and mark correlation function, address this limitation by using a ring of width w rather than a circle of radius r, calculating average point numbers within rings to isolate specific distance classes. As a probability density function, O-ring statistics more intuitively reflect distribution patterns at specific scales [?]. Both univariate and bivariate statistics are included: univariate O(r) statistics analyze single-object distribution patterns, while bivariate $O_{12}(r)$ statistics examine patterns between two objects. The statistics are calculated as follows:

For univariate O-ring statistics:

$$\hat{O}_{11}(r) = \frac{1}{n_1} \sum_{i=1}^{n_1} \frac{\text{Points}_1[R_{w,1,i}(r)]}{\text{Area}[R_{w,1,i}(r)]}$$

For bivariate O-ring statistics:

$$\hat{O}_{12}(r) = \frac{1}{n_1} \sum_{i=1}^{n_1} \frac{\text{Points}_2[R_{w,1,i}(r)]}{\text{Area}[R_{w,1,i}(r)]}$$

where n_1 is the number of individuals in population 1, R_{w,1,i}(r) is a ring around the ith point of population 1 with radius r and width w, Points_1[R_{w,1,i}(r)] and Points_2[R_{w,1,i}(r)] are the numbers of individuals from populations 1 and 2 within the ring, respectively, and Area[R_{w,1,i}(r)] is the ring area (m^2).

In this study, univariate O-ring analysis was applied to all recruits (seedlings and saplings), while bivariate analysis examined spatial correlations between recruits and canopy trees and between seedlings and saplings. O-ring statistics require careful null hypothesis selection [**?**, **?**]. For univariate recruit analysis, complete spatial randomness (CSR) served as the null model—the simplest and most widely used model, assuming equal probability of point occurrence at any plot position and independent point locations [**?**].

For bivariate analysis, two situations were considered. When analyzing different age classes (recruits and canopy trees), we assumed these represented sequential temporal events, where canopy tree pattern development would not influence recruits, but recruit development might be influenced by canopy trees [**?**]. Here, null model selection was guided by antecedent conditions [**?**]. For investigating recruit-canopy tree relationships, an appropriate null model randomized recruit locations while keeping canopy tree positions fixed, because canopy trees were already present and immobile during recruitment establishment, while recruits could potentially occur anywhere in the plot [**?**, **?**]. Thus, an antecedent condition null model tested whether recruit pattern formation was influenced by canopy tree patterns. When comparing seedlings and saplings, an independence null model was applied, assuming their spatial patterns resulted from two independent stochastic processes (e.g., different dispersal periods) [**?**, **?**].

These analyses were performed using Programita software. Statistical significance of O(r) departures from randomness was tested via Monte Carlo simulations using three null models: CSR, antecedent condition, and independence. Confidence envelopes were obtained from the highest and lowest function values across 99 null model simulations.

3.1 Composition of Tree Species

Tree species analysis across all plots revealed Chinese pine as the dominant species (Table 3), exceeding 90% proportion in all plots except NB1. Accompanying species composition differed before and after clear-cutting, with shade-tolerant Mongolian oak and hawthorn (*Crataegus pinnatifida*) present only in EB1 and NB1 plots. Post-clear-cutting, more shade-intolerant pioneer species such as aspen were observed. Slope aspect had minimal effect on species composition (Table 3).

3.2 Density of Recruits

Advanced recruit densities were 7,886 and 5,036 stems/hm^2 in EB1 and NB1 (one year before clear-cutting), respectively. Post-clear-cutting, recruit density increased significantly in the first two years, then gradually decreased, stabilizing between eight and eleven years (Fig. 2 [FIGURE:2]). Density differed significantly between east- and north-facing slopes, with higher densities on east-facing slopes (Fig. 2). Specifically, recruit density increased by 15.90%-56.59%, with NA5 plot density 18.04% higher than EA5 plot (Fig. 2).

3.3 Height of Recruits

In pre-clear-cutting plots, average recruit heights were 0.78 ($±0.85)mand1.06(±1.15)mforEB1andNB1,respe clear − cutting, averageheightincreasedgraduallyovertime(Fig.3[FIGURE : 3]), reachingfinalheightsof2.00(±1.14)mand2.24(±$1.20) m in EA11 and NA11 plots—significant increases of 156.00% and 110.80% (P<0.01). Slope aspect significantly influenced recruit height (Fig. 3), with north-facing slopes supporting greater heights than east-facing slopes (P<0.01 for all comparisons). Height distribution was also significantly affected by slope aspect, showing greater decentralization on north-facing slopes (Fig. 4 [FIGURE:4]).

3.4 Diameter at Breast Height (DBH) of Recruits

Pre-clear-cutting average DBH values were 3.21 ($±1.38)cmand2.91(±$1.38) cm for EB1 and NB1, respectively. Post-clear-cutting, average DBH initially decreased, then gradually increased, stabilizing between eight and eleven years (Fig. 5 [FIGURE:5]). Slope aspect significantly influenced DBH: pre-clear-cutting, EB1 exceeded NB1 (P=0.015), but post-clear-cutting, north-facing plots consistently showed higher DBH than east-facing plots (P<0.01 for all; Fig. 5).

3.5 Age of Recruits

Pre-clear-cutting average ages were 8.44 ($±4.49)and7.38(±2.88)yearsforEB1andNB1,respectively.Twoyear clear−cutting, averageagesdecreasedto5.86(±1.08)and7.05(±1.74)yearsforEA2andNA2(P < 0.01andP = 0.142; Fig.6[FIGURE : 6]), thengraduallyincreasedovertime.Slopeaspectaffectedage : pre − clear − cutting, EB1exceededNB1(P = 0.017), butpost − clear − cutting, north − facingplotsshowedhigheragesthaneast − facingplots(P $0.01, except P=0.13 between EA11 and NA11; Fig. 6). In two-year post-clear-cutting plots, recruits originating from advanced regeneration comprised 100% and

98.32% of total recruits for EA2 and NA2, respectively (Table 4). This proportion gradually declined over time, reaching 33.33% and 38.05% in EA11 and NA11 plots (Table 4).

3.6.1 Univariate Distribution Patterns

Spatial recruitment patterns were strongly influenced by time and slope aspect. Univariate analysis revealed aggregation at small scales during most developmental stages (Fig. 7 [FIGURE:7]). On east-facing slopes, recruits remained aggregated at small scales, with clumped patterns observed up to 9, 9, 6, 12, and 9 m for EB1, EA2, EA5, EA8, and EA11 plots, respectively (Figs. 7a, c, e, g, i). On north-facing slopes, spatial patterns varied developmentally: NB1 and NA2 recruits showed clumped patterns up to 11 and 7 m (Figs. 7b, d); NA5 recruits exhibited clumping only at very small scales (0–2 m) and random patterns elsewhere (Fig. 7f); NA8 recruits showed random patterns at 2–14 m and regular patterns at larger scales (Fig. 7h); NA11 recruits were clumped at all scales (Fig. 7j). Aggregation intensity decreased gradually from two to eight years post-clear-cutting on both aspects (Figs. 7c–h).

3.6.2 Bivariate Association Patterns

Recruitment spatial patterns were simultaneously influenced by multiple factors. Bivariate analysis examined associations between recruits and canopy trees and between seedlings and saplings. In EB1 and NB1 plots, recruits were spatially independent of canopy trees (Figs. 8a, b).

Spatial correlation between seedlings and saplings shifted from attraction to independence over time. In EB1 and NB1, spatial attraction occurred at 0–6 and 0–11 m scales, independence at 7–9 and 12–14 m, respectively, then shifted to repulsion at larger scales (Figs. 9a, b). In EA2, attraction extended to 24 m with repulsion beyond (Fig. 9c), while NA2 showed attraction at 0–6 m, independence at 7–13 m, and repulsion at 14–30 m (Fig. 9d). EA5 exhibited positive correlation up to 28 m (Fig. 9e), but NA5, EA8, NA8, EA11, and NA11 showed independence at all scales (Figs. 9f–j).

4.1 Composition of Tree Species

Natural recruitment was dominated by Chinese pine, exceeding 90% proportion in most plots (Table 3). Few seed sources of other native species (aspen, elm (*Ulmus pumila*), black locust, Mongolian oak) were observed near stands. On the Loess Plateau, sufficient Chinese pine seed resources exist, but other native species' recruitment is limited by thick litter covering emerging seedlings [**?**]. Clear-cutting accelerates litter decomposition and reduces litter sources, decreasing this limitation over time. Seed sources then become the main limiting factor, supported by studies showing higher proportions of other tree species when clear-felled plantations are surrounded by diverse seed sources [**?**, **?**].

4.2 Density of Recruits

Recruit density increased significantly two years post-clear-cutting (Fig. 2), indicating that clear-cutting promotes seedling germination. Environmental factors changed correspondingly, including increased light intensity and soil temperature and decreased litter thickness and Chinese pine autotoxicity [?, ?]. The subsequent gradual density decrease resulted from high recruit mortality due to lack of drought and heat protection post-clear-cutting [?], exacerbated by intense competition for nutrients, water, and space causing self-thinning.

Slope aspect significantly affected recruit density. Pre-clear-cutting, EB1 density was 56.59% higher than NB1 (Fig. 2), consistent with previous findings [?, ?] that east-facing slopes provide better light and heat conditions for Chinese pine germination and survival. Post-clear-cutting, water availability became the main limiting factor. With limited annual precipitation (356.7–620.3 mm; Table 1) and reduced soil moisture after clear-cutting, north-facing slopes became more suitable for germination and survival. However, recruit density remained higher on east-facing slopes post-clear-cutting (except EA5 and NA5; Fig. 2), contrary to expectations and warranting further investigation.

4.3 Height and DBH of Recruits

Both the quantity and proportion of saplings (>0.5 m) two years post-clear-cutting significantly exceeded pre-clear-cutting levels (Fig. 2; Figs. 4a–d). Previous studies also found that clear-cutting promotes Chinese pine recruit height growth [?]. Chinese pine recruit development involves temperature-required and light-required phases; four-year-old seedlings enter the light-required phase, so sapling growth is promoted by increased light after clear-cutting [?]. Reported densities, average heights, and DBH of 11-year-old Chinese pine plantations on north- and northeast-facing slopes are approximately 1,500–2,000 stems/hm^2, 2.3–3.0 m, and 2.1–2.8 cm, respectively [?]. In our study, recruit densities (height $ 2.3m)were1, 536and1, 725stems/hm^{2}$, with corresponding average DBH of 3.6 and 3.8 cm in EA11 and NA11 plots. We therefore conclude that natural recruitment enables faster forest restoration than artificial afforestation.

Since recruit density and average DBH did not vary significantly between eight and eleven years post-clear-cutting (Figs. 2, 5), DBH did not increase correspondingly with height. During this interval, self-thinning effects were minimal, and existing density hindered sapling growth, indicating that artificial thinning is necessary eight years post-clear-cutting. The proportion of taller recruits declined dramatically in EA2 and NA2 compared to EB1 and NB1 (Fig. 4), suggesting damage to advanced regeneration by clear-cutting.

4.4 Age of Recruits

Slope aspect significantly affected recruit age (Fig. 6), consistent with previous studies [?, ?]. Pre-clear-cutting, NB1 average age was lower than EB1 (Fig.

6) because light limitation was more severe for light-phase recruits in NB1 [?]. Post-clear-cutting, north-facing plots consistently showed higher average ages than east-facing plots (Fig. 6), attributable to harsher conditions and higher mortality on east-facing slopes. The proportion of recruits originating from advanced regeneration gradually declined over time (Table 4), reaching only 33.33% and 38.05% in EA11 and NA11 plots, respectively. However, these recruits' average heights reached 3.25 ($±1.13)*mand*2.99(±$1.07) m (Table 4), indicating their vital role in creating shade and improving microclimate. This suggests that advanced regeneration plays significant roles throughout forest recovery stages after clear-cutting.

4.5 Spatial Point Pattern

Recruits predominantly exhibited aggregated distribution at small scales (Fig. 7), a pattern widely observed in natural regeneration studies [?, ?, ?, ?, ?]. This aggregation relates to both favorable patch distribution and wind-dispersed seed characteristics of Chinese pine. Wind dispersal efficiency is strongly affected by wind and surrounding trees, promoting aggregated distribution [?, ?], which helps create near-natural forest structure. Maximizing structural diversity and wildlife value requires 20%–50% open space in forest land [?]. Aggregation scales did not exceed 12 m in all plots except NA11 (Fig. 7), limited by Chinese pine seeds' inability to disperse long distances without auxiliary flying structures. Aggregation intensity decreased gradually from two to eight years post-clear-cutting due to self-thinning (Figs. 7c–h), as increased recruit size intensified resource competition among neighbors.

Recruits and canopy trees were spatially independent (Fig. 8). Studies have found that pre-clear-cutting, environmental factors are more important than density-dependent mortality [?] and canopy tree nurse effects [?]. At low stand ages, recruits may be positively related to canopy trees due to dispersal limitation and nurse effects, but this relationship changes over time with increasing competition [?]. Post-clear-cutting, seedlings were positively correlated with saplings briefly (Figs. 9c–e), indicating that saplings' shade environment benefited seedlings.

5 Conclusions

Advanced recruitment density in Chinese pine plantations is extremely high with substantial potential, which is quickly released after clear-cutting. Recruits exhibit better growth on north-facing than east-facing slopes post-clear-cutting. Considering recruit density, height, and DBH, natural recruitment enables faster restoration within eleven years post-clear-cutting than artificial afforestation. Recruit height distribution indicates that naturally regenerated forests have higher vertical structural diversity than single-storied, even-aged plantations. The predominantly clumped recruitment pattern also suggests higher horizontal structural diversity than uniformly planted plantations. Thus, natural recruitment offers faster restoration and higher structural diversity than artificial afforestation in early forest recovery stages, potentially producing forests with high economic, ecological, and landscape value at substantially reduced cost. We propose that clear-cutting Chinese pine plantations with natural recruitment recovery represents a promising and effective method for establishing multifunctional forests.

However, forest recovery is a long-term process, and since clear-cutting has only been applied since 2003, continued observation is needed to explore temporal and spatial variation trends in natural recruitment. Based on our results, we recommend: (1) artificial thinning eight years post-clear-cutting; (2) protection of advanced regeneration during clear-cutting operations due to its important early-stage role; and (3) artificial disturbance to increase species diversity, such as supplementary planting of other native species and retaining accompanying species during thinning.

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