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Impact of Initial Planting Density on the Optimal Economic Rotation of Chinese Fir (*Cunninghamia lanceolata* (Lamb.) Hook) in an Experimental Forest Plantation

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Abstract: The amount to be invested and the timing of clearcutting are central concerns in timber production. To assess the impact of the initial planting density on optimal economic rotation, we explicitly included the distribution of stand diameter classes and price differences representing the quality of stumpage in a model of forest land expected value (LEV). We selected five initial planting densities of 35-year old China fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantations to fit the distribution of diameter classes along with stand age using a three-parameter Weibull theoretical growth model and then the Faustmann formula was used to calculate LEVs under different conditions. We found that the difference in the values of the growth rate of the stand volume and the discount rate affected the direction of the impact of initial planting density on the optimal economic rotation. If the value of the growth rate of the stand volume exceeded that of the discount rate, then the initial planting density had a negative impact on optimal economic rotation and vice versa. In addition, the quality effect, which means the shift in diameter class to a higher value attributed to the initial planting density, determined the extent of the impact of the initial planting density on the optimal economic rotation. The proportion of large-sized timber increased at a faster pace in accordance with the age of the stand in stands where the planting density was low compared with the proportion of such timber in stands with a higher initial planting density. The corresponding net stumpage price difference resulted in significant differences in LEVs. We concluded that a low-density stand of China fir was a preferred planting option for obtaining the highest LEV.

Keywords: Chin fir; initial planting density; optimal economic rotation period; discount rate; stumpage price

1. Introduction

The Chinese fir is one of the most important timber species in southern China because of its predominance in its areas of distribution and the total accumulated standing timber volume. This species is widely used in construction, shipbuilding, mining pit timber, agricultural tool production, and for decorative purposes [1]. Commencing with the sixth five-year science and technology support project initiated by the Chinese government in the 1980s, a silvicultural system for managing industrial timber forests comprising Chinese fir gradually evolved. The core underlying principles of this system are regulating genetic gains, stand densities, and site conditions, with the aim of achieving increasing timber production through intensive forest management. Critical aspects of this intensive

forest management system include choices of the initial planting density, which determines inputs for timber production, and of the optimal rotation period, which enhances outputs. This input–output relationship impacts the efficiency of forest production. Therefore, a theoretical analysis of forest management and of production practices associated with variations in initial planting density and rotation period is essential.

There is extensive literature on optimal economic rotation [2–10]. Thus, studies on Chinese fir plantations have examined timber utilization goals [11], stumpage prices [12], and stand density control [13] in depth. Economic indicators, such as the interest rate and price and technical indicators, such as silvicultural measures, vary according to the research objectives. Moreover, while initial planting densities indicated in previous studies may be beneficial for some Chinese fir management regimes, depending on specific conditions, the impacts of changing market conditions on revenues from Chinese fir production remain unclear. Therefore, a study of the dynamics of optimal rotation periods under different economic and technological conditions is pertinent.

Although the initial planting density is widely considered by forest scientists to impact critically on stand growth dynamics, there are few studies on its effect on forest management [14]. There are three considerations relating to the role of the initial planting density, as follows. First, the initial planting density can affect the timber quality [15,16]. There are significant differences in the distribution of stand diameter classes resulting from different initial planting densities. A decrease in the initial planting density corresponds to an increase in the proportion of large-sized timber and, consequently, to better timber quality [17]. Second, the initial planting density can affect the profitability of timber production [18] because increases in the diameter classes lead to higher stumpage prices. At the same time, increases in the diameter classes are associated with reductions in the harvest costs, leading to significant differences in the net price of stumpage, with higher initial planting densities corresponding to lower stumpage prices and higher harvest costs. Therefore, stands with higher proportions of large-sized timber will be more profitable than those with lower proportions. Third, the initial planting density can determine the timing and intensity of thinning operations [18,19]. Consequently, the stand density effect should be explicitly included in the optimization model.

Chang [20] analyzed the influence of the initial planting density on the profitability of timber production. Chang's model, which was derived from that of Faustmann and from early studies by Hyde [21] and Hirshleifer [22], entailed a reduction of the multiple effects of interactive structures emanating from different planting densities in relation to economic aspects. Most subsequent studies have applied Chang's framework to analyze the relationship between the initial planting density and optimal economic rotation [23,24]. However, when analyzing the relationship between the planting density and optimal economic rotation, Chang did not consider price differences [20]. In a study of the impact of European Scots pine timber, differentiated by quality, on stumpage prices, Zhou examined price differences in stumpage [25]. Following Zhou, Brazee, and Dwivedi examined the relationship between timber quality and stumpage price in a study of the optimal rotation period. They found that the stumpage prices for timber of different diameter classes directly affected optimal economic rotation. A larger timber diameter class corresponded to a higher stumpage price. Moreover, increasing the stumpage price extended the optimal economic rotation [9]; a finding that contradicted those derived from static analyses of the original Faustmann model (In a comparative static analysis of the Faustmann model, Amacher et al. showed that an increase in the stumpage price shortened the optimal rotation period, providing that other conditions remain unchanged [26]).

A further consideration is that Chang did not account for thinning when analyzing the relationship between initial planting densities and optimal economic rotations. The assumption in this study was that any expansion in the planting density and optimal economic rotation models, for example, through the inclusion of thinning, would increase the model's complexity, which might not then yield meaningful results [20]. Following Chang's study, although some forest scientists combined the initial planting density, thinning, and the optimal economic rotation period within the same analytical framework [2,14,19,27,28], no consistent conclusions about their relationship was reached.

For example, some forest scientists have posited that initial stands developed in coniferous industrial timber forest plantations should be of high initial density to ensure enhanced operating incomes through tending and thinning [24,29–32]. Other studies have suggested the opposite, arguing that the planting of coniferous timber forest plantations should be directly related to the final clearcutting stand density [18,25,33]. Early studies on the thinning of Chinese fir plantations conducted by Jiang et al. [34] and Liu et al. [35] suggest that thinning could improve timber quality as well as the merchantable stand volume and increase operating incomes. However, annual increases in labor prices result in continuously increasing labor costs associated with tending and thinning, which may even exceed the incomes derived from these operations. Observations conducted in many Chinese fir plantations have revealed that no thinning had been conducted in stands, even in cases where canopy closure and stand self-thinning were evident. In their study of Nordic Scotch pines, Hyytiäinen et al. pointed out that careful consideration should be given to sorting norms and price ratios under different conditions. In particular, high interest rates often rule out a high initial planting density, even when thinning is optional, because the additional income stream may be generated too late [15]. The results of a study on thinning intensities in Chinese fir plantations, conducted by Zhang et al. [36], showed that thinning could promote diameter growth and increase individual tree volumes, but it did not enhance the total standing timber volume. Therefore, the only way to improve the efficiency of forest production was to reduce the cost by reducing the labor input, as the total standing timber volume would remain constant.

Referring to existing research findings, we examined the relationship between the initial planting density and the optimal economic rotation period in the absence of thinning. To avoid the influences of other silvicultural factors, we established the following assumptions:

- (1) Differences in site conditions were not considered in this study. According to the technical silvicultural regulations for Chinese fir plantations with large-sized timber (LY/T 2809-2017), the site indexes of Chinese fir plantations must not be less than 16. The site indexes of the experimental forest plantations constructed in this study were all 18.
- (2) Management measures such as controlling competing vegetation were not considered. The production cost of competing vegetation control for two consecutive years after Chinese fir seedling planting and tending and thinning operations prior to canopy closure were also not considered.
- (3) All random events (e.g., climate-related disasters, plant diseases, revival of planting seedlings, and replanting), which were directly related to planting techniques, soil preparation, and seedling survival, were ignored.
- (4) The effects of taxes and fees were not considered.

The importance of all the factors excluded from the analysis, which affect the quantity and quality of timber outputs, was not discounted. However, they were not considered relevant to the topic under investigation, namely the effect of initial planting density on the optimal economic rotation period of Chinese fir plantations.

2. Method

This study was based on Chang's analytical framework used to explore the relationship between the initial planting density and optimal economic rotation. In an analysis of the effects of planting density and rotation, Chang [20] established the following model of forest land expected value (LEV):

$$\max_{T,m} LEV^c = \frac{pQ(T, m) - C_f - C_v m}{e^{rT} - 1} - C_f - C_v m \quad (1)$$

where Q denotes the standing timber volume, which varied with the final harvesting age (T) and the initial planting density (m); C_f denotes the fixed cost associated with planting; C_v denotes the variable cost of planting; LEV^c is the expected value of forest land; p is the stumpage price; and r is the discount rate.

Although Chang proposed a basic relationship between these two variables, he did not consider the impact of the initial planting density on the distribution of diameter classes in a stand. The initial planting density of Chinese fir plantations does not have a significant effect on the total standing timber volume of a stand (the standing timber volume increases with the initial planting density in younger forest plantations) [37]. Density-dependent mortality from self-thinning occurs in forest plantations with a higher planting density when tending and thinning are applied [38]), but it does have a significant effect on the distribution of the diameter classes within a stand [38]. The stumpage prices of the Chinese fir plantations vary with diameter classes. A larger diameter class corresponds to a higher stumpage price. Moreover, under the condition of a prevailing final harvesting technology of a certain level, a larger diameter class corresponds to a lower harvesting cost. Therefore, differences in the stumpage prices originate from the initial planting densities, resulting in significant differences in the forest *LEVs*, and these differences are also accentuated by harvesting costs [14]. For example, assuming that other conditions are the same, the smaller diameter class, which is lower in price but entails a higher harvesting cost, occupies a large proportion of timber in a stand with a high initial planting density, implying that the forest *LEV* would not be high. Therefore, the net price differences for a stand (the stumpage price minus the harvesting cost) must be considered in the management of Chinese fir plantations.

Applying Chang's model, Coordes [14] set the stumpage price (p^j) in relation to the timber diameter class (j) exogenously. The harvest cost (c) depended on the initial planting density (m), the rotation period (T), and the diameter class (j); S^j denoted the ratio of j to the total standing timber volume in the stand. Thus, the stumpage value within a stand was calculated as follows:

$$V(T, m) = \sum_{j=1}^n [p^j - c^j(T, m)] S^j(T, m) Q(T, m) \quad (2)$$

To simplify Equation (2), we introduced p^j , denoting the net price of the stumpage, and Q^j , indicating the volume of diameter class j :

$$V(T, m) = \sum_{j=1}^n p^j Q^j(T, m) \quad (3)$$

Equation (3), used to calculate the stumpage value, was incorporated into Chang's model and a maximum expected value of forest land (LEV^E) was obtained:

$$\max_{T, m} LEV^E = \frac{V(T, m) - C_f - C_v m}{e^{rT} - 1} - C_f - C_v m \quad (4)$$

For Equation (4) to reach the maximal level, its first-order derivations of T and m needed to be satisfied, as indicated in Equations (5) and (6):

$$\frac{\partial LEV^E}{\partial T} = 0 \Big|_{(T^*, m^*)} \Leftrightarrow V_T = rV + rLEV^E \quad (5)$$

$$\frac{\partial LEV^E}{\partial m} = 0 \Big|_{(T^*, m^*)} \Leftrightarrow V_m = C_v e^{rT} \quad (6)$$

The first-order condition of the forest *LEV* was closely aligned with the well-established Faustmann–Pressler–Ohlin theorem [39]. In terms of the optimal economic rotation, as shown in Equation (5), the value increment of a stand (on the left-hand side of the equation) balanced the capital cost of stumpages and the forest land (on the right-hand side of the equation). The characteristics of the optimal initial planting density were similar. As Equation (6) shows, because of the increase in the number of trees planted, the optimal initial planting density balanced the future variable cost and

the value increment. It is noteworthy that Equations (5) and (6) are mutually dependent; any changes in the initial plant density could affect the maximal condition of the optimal economic rotation period and vice versa as a result of changes in the stumpage value.

The above model demonstrates two important aspects of optimal initial density. First, the initial planting density evidently determined the proportional distribution of the standing timber volume for different diameter classes. Second, the planting density determined the net stumpage price. However, it is important to note that general recommendations on optimal initial planting density cannot be made in the case of simultaneous changes in the stumpage price and the discount rate. Therefore, in the following theoretical analysis, the effects of exogenous parameters were not examined separately; rather, the endogenous mutual dependence of the initial planting density and the rotation period was analyzed.

Applying the necessary first-order condition calculated using Equation (5), this equation can be rewritten in a different form as follows:

$$\sum p^j Q_T^j + \sum p_T^j Q^j = r \sum p^j Q^j + rLEV \quad (7)$$

Assuming an optimal choice of the set of decision variables $\{T, m\}$, the first-order condition (7) was applied in a comparative analysis of the influence of m on T . Differentiating Equation (7) in terms of m and T results in the following:

$$\begin{aligned} \frac{\partial^2 LEV}{\partial T^2} dT + \frac{\partial^2 LEV}{\partial T \partial m} dm &= 0 \\ \frac{dT}{dm} &= - \frac{\frac{\partial \sum p^j Q^j}{\partial m} (\sum Q_T^j / \sum Q^j - r)}{\frac{\partial^2 LEV}{\partial T^2}} \end{aligned} \quad (8)$$

As revealed by Equation (8), the effect of the initial planting density on the optimal economic rotation period, T^* , could not be simply identified as positive or negative; the relationship was a highly complex one. However, under certain conditions, it was possible to determine their relationship. First, an overall “concave” forest LEV function was definitively associated with a negative $\partial^2 LEV / \partial T^2$ value for the rotation period [40]. Second, the initial planting density had a negative impact on the stumpage value, that is, the value of $\partial \sum p^j Q^j / \partial m$, which denotes the marginal value of the planting number, was also negative. Therefore, the difference in the values of growth rate of standing timber volume and the discount rate, that is, $\sum Q_T^j / \sum Q^j - r$, determined whether the relationship between the initial planting density and T was positive or negative. In the case of a higher growth rate of standing timber volume, the initial planting density had a negative effect on T . In this density-dependent price model, T^* could occur at a later stand age if $\sum Q_T^j / \sum Q^j < r$, that is, the difference in the values of the growth rate of standing timber volume and the discount rate is above 0. In this case, the effect of the initial planting density on T would be positive. As the cross-derivative value could not be determined conclusively, the calculation based on long-term observation data could be used to indicate the effect of initial planting density on optimal economic rotation in a particular situation.

3. Materials and Methods

Observational data compiled for an experimental plantation on the density of 35-year old Chinese fir trees were used in this study. The experimental forest was established at the Subtropical Forest Experimental Center (27°34' N, 114°33' E) in Fenyi City, Jiangxi Province. In the spring of 1981, 1-year-old Chinese fir bare root seedlings were planted. A randomized block design was applied, with planting spaces of 2.0 m × 3.0 m (1667 seedlings/ha), 2.0 m × 1.5 m (3333 seedlings/ha), 2.0 m × 1.0 m (5000 seedlings/ha), 1.0 m × 1.5 m (6667 seedlings/ha), and 1.0 m × 1.0 m (10,000 seedlings/ha). These five initial planting densities formed a block, with each initial planting density replicated three times. Each plot comprised an area measuring 20 m × 30 m and a buffer zone containing similarly treated

trees surrounded each plot. The trees in all the plots were numbered and the following measurements were taken annually from the third year following planting. After 10 years, the frequency of surveys on forest growth conditions was altered to once every 2 years. A total of 23 continuous observations had been recorded up to the end of 2018.

The distribution of diameter classes constitutes the basis for the grading and utilization of timber. In this study, the three-parameter Weibull theoretical growth model was used to analyze the distribution of diameter classes along with stand age under different initial planting densities. First, diameter classes were divided by each 2 cm diameter class and the diameter class distribution of 15 plots were illustrated along with stand age. The stand age was taken as the independent variable and the standing timber volume, corresponding to different classes, was the dependent variable at a confidence level of 95%. The maximum likelihood estimation method was used iteratively to fit the Weibull parameter. The results of estimated parameters obtained using the R software are shown in Table 1.

Table 1. Estimation results for the three-parameter Weibull model.

Initial Planting Density (Seedlings/Ha)	Parameter A	Parameter b	Parameter c	Value	Counts (Gradi)	R ²	RMSE
1667	361.800	13.460	2.080	0.026	97	0.913	36.616
3333	369.664	12.471	2.088	0.017	288	0.888	43.137
5000	416.376	14.540	1.892	0.004	610	0.977	19.701
6667	398.204	15.012	2.009	0.003	1000	0.994	9.642
10,000	588.869	18.199	1.669	0.011	1000	0.983	19.774

We calculated the timber volume of different diameter classes at stand ages of 5, 10, 15, and 20 years to enable a comprehensive assessment of the impact of the initial planting density on the diameter class and timber volume. As Figure 1 showed, a lower initial planting density was associated with a distribution curve moving faster to the right than the curve for a higher initial density and an increasing diameter class. A large proportion of the standing timber volume in stands where initial planting densities were higher comprised timber of small diameter classes. The proportion of large-sized timber in stands where initial planting densities were lower increased at a faster rate compared with the proportion of such timber in stands where initial planting densities were higher. Moreover, the standing timber volume of medium-sized timber increased with stand age, but the volumes of medium-sized timber were relatively close among stands of the same age but with different initial planting densities.

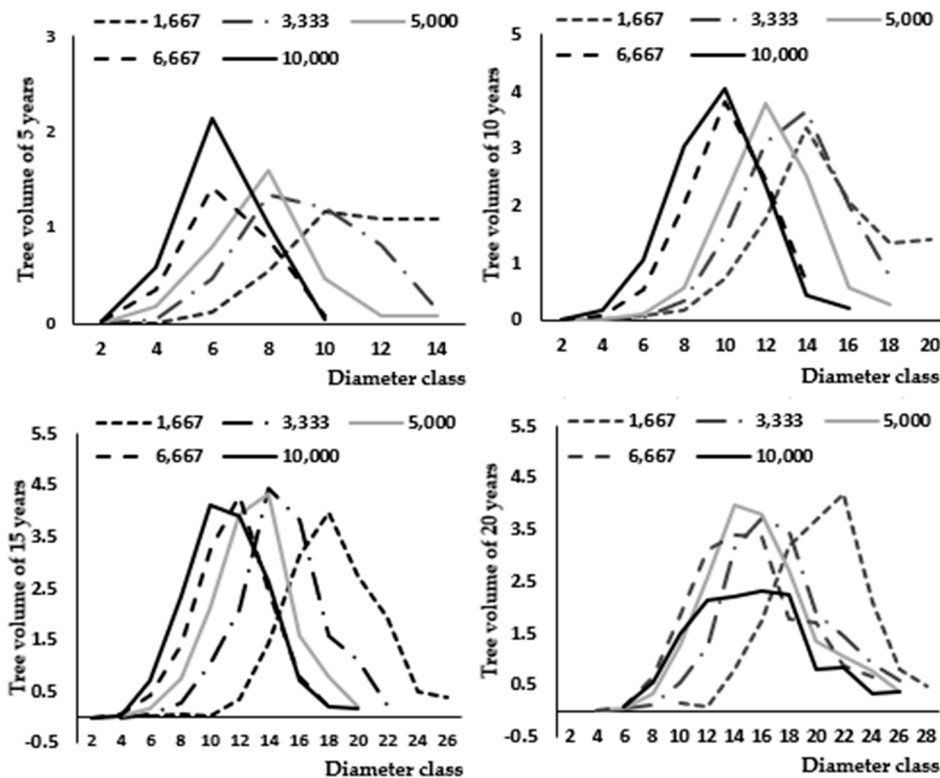


Figure 1. The distribution of standing timber volumes in a Chinese fir plantation by diameter class at the ages of 5, 10, 15, and 20 years.

The growth rates of the standing timber volume in stands with different initial planting densities were calculated using the fitted Weibull equation (Figure 2). During the early growth stage, stands with higher initial planting densities evidenced a slower standing timber volume growth rate than those with lower initial planting densities. After 10 years of growth, the growth rates of the standing timber volume under different initial planting densities were below 0.1. When the stand reached an age of about 13 years, the growth rates of the standing timber volume were below 0.05 and were asymptotically equal to 0. These findings are basically consistent with those of Zhang et al. [36,41], who examined the growth of Chinese fir in a plantation.

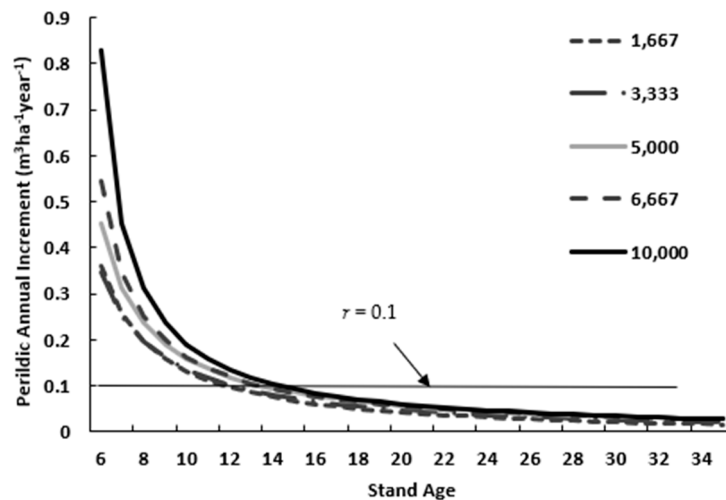


Figure 2. The periodic annual increment in a Chinese fir plantation.

The value T^* was calculated using Equation (6) and the stumpage values were calculated by multiplying the standing timber volumes of different diameter classes by the corresponding net stumpage prices. As there are currently no published price series data for timber assortments in China, data on stumpage prices were obtained from statistical summaries of prices provided for southern provinces of China [12]. Information on costs was based on the actual situation (see Table 2). The initial planting costs ranged from 5833 yuan to 10,000 yuan per hectare, depending on specific initial planting densities. The average harvesting cost in relation to all the initial planting densities was 208.27 yuan/m³.

Table 2. Timber prices, harvesting costs, and net prices of plantation-harvested Chinese fir (unit: yuan/m³).

Diameter Class	6–8	10–12	14–16	18–20	22–24	26–28	>30
Stump price	600	900	1150	1450	1650	1900	2150
Harvesting cost	333.50	251.70	208.40	190.70	172.50	148.80	137.90
Net price	266.50	648.30	941.60	1259.30	1477.50	1751.20	2012.10
Variable cost of planting (Yuan/tree number) 0.5							
Fixed cost of planting (Yuan/ha) 8000							

4. Results

4.1. The Expected Value of Forest Land and Optimal Economic Rotation Under Different Initial Planting Densities

The optimal economic rotations for different initial planting densities were calculated using Equation (6). Table 3 presents a summary of the results of the calculation. As there was some uncertainty regarding the selection of the discount rate, this rate was set at values ranging between 0.01 and 0.09, as clarified in the discussion section of this paper. Following other authors, such as Halbritter and Deegen [40], the results presented in Table 3 only show *LEVs* and stumpage values for Chinese fir plantations using a discount rate of 0.05. The value T^* first decreased and then increased with an increasing initial planting density. The optimal rotation periods were closer and longer for stands with the highest and lowest initial planting densities than they were for stands with initial planting densities that were in between these values. The initial planting density of 1667 seedlings/ha resulted in the highest stumpage value at the point of T^* , while this value was lowest for initial planting densities of 5000 seedlings/ha and 6667 seedlings/ha. Stumpage values for initial planting densities of 3333 seedlings/ha and 10,000 seedlings/ha were midway along this spectrum. Accordingly, the selected initial planting density should be between the two extremes of low-density or high-density planting. However, when the capital cost of investment was considered, the forest *LEV* evidenced a declining trend, with the initial planting density increasing, which resulted in our preference for low-density planting. The capital cost of land also includes its rent and the entailed interest incurred for forest land managers. The capital cost for stumpage arises from delays in clearcutting. These two costs together constitute the maximum opportunity costs that are incurred by forest land managers. Table 3 shows that the highest opportunity cost was incurred for stands with the lowest planting density, with the marginal revenue generated by these stands being the highest. The stands with middle-density planting yielded the lowest marginal revenues. The plantation managers would thus have to delay clearcutting Chinese fir trees until a stage is reached when the increment of marginal forest land revenue no longer exceeds the total opportunity cost [42]. Table 3 shows when optimal economic rotation, calculated using the procedure of extending the Faustmann model, discussed in this paper, would occur.

Table 3. The stumpage values, *LEV*s, and optimal economic rotation lengths for an experimental Chinese fir plantation (discount rate $r = 0.05$).

Initial Planting Density (Seedlings/Ha)	Optimal Rotation (Year)	Stumpage Value (Yuan/Ha)	Land Expected Value (Yuan/Ha)	Capital Cost of Land (Yuan/Ha)	Capital Cost of Stumpage (Yuan/Ha)
1667	16	13,897.333	5142.600	507.130	694.867
3333	13	9042.338	4599.429	479.971	452.117
5000	13	7203.396	2842.951	392.148	299.020
6667	16	8646.617	1229.049	311.452	297.831
10,000	17	9099.256	1561.001	328.050	454.963

We used a value of $r = 0.05$ to illustrate the calculation of the forest *LEV* and the optimal economic rotation period in a Chinese fir plantation. These results clearly reflect the complexity and importance of the initial planting density and its impact on forest management. In the following section, a more detailed analysis of the stand density effect is presented.

4.2. The Initial Planting Density and Optimal Economic Rotation Under Different Discount Rates

An analysis of the results calculated using Equation (8) revealed whether the impact of the initial planting density on T^* was positive or negative. These values were contingent on differences in the values of the growth rate of standing timber volume in a stand and the discount rate at that time. The choice of a discount rate is a highly controversial issue. Given uncertainty about the future, decreasing marginal benefits relating to consumption, and capital opportunity costs, a higher discount rate should be selected. However, many scholars who are concerned about the limited growth of natural resources and intergenerational equity have opposed the setting of a higher discount rate [43,44], with some even suggesting that negative discount rates should be chosen [45]. We set nine discount rates ranging from low to high and applied sensitivity analysis to show the changes rule of T^* under conditions of different discount rates and initial planting densities. Table 4 shows the results of the sensitivity analysis. These results indicate that at the same initial planting density, T^* decreased with an increase in the discount rate, which is consistent with the results of the static comparative analysis of the basic Faustmann model [26]. An increase in the discount rate simultaneously raises the capital cost incurred by delaying the final harvesting. A higher discount rate corresponds to a lower value of future harvesting. Consequently, the final harvesting is more likely to be conducted earlier. Evidently, the discount rate has a specific effect on final forest harvesting decisions, determining the final harvesting rate for forest timber resources. Our results also indicated that when a lower discount rate was applied, differences in T^* values for different initial planting densities were small, whereas differences in these values increased with a rise in the discount rate.

Table 4. Calculated values of T^* (*LEV*) for an experimental Chinese fir plantation using different initial planting densities and discount rates.

Initial Planting Density (Number/Ha)	$r = 0.01$	$r = 0.02$	$r = 0.03$	$r = 0.04$	$r = 0.05$	$r = 0.06$	$r = 0.07$	$r = 0.08$	$r = 0.09$
1667	20 (39,445)	18 (27,385)	17 (20,557)	17 (6106)	16 (5142)	15 (4828)	13 (3381)	11 (2521)	8 (2041)
3333	19 (33,579)	16 (24,874)	15 (18,409)	15 (5846)	13 (4599)	12 (4001)	11 (3079)	10 (2484)	9 (1962)
5000	18 (27,887)	15 (19,392)	15 (14,523)	14 (4744)	13 (2842)	13 (2409)	11 (2165)	11 (1987)	10 (1538)
6667	19 (26,191)	18 (18,674)	17 (12,331)	17 (3568)	16 (1229)	14 (1067)	13 (891)	13 (742)	13 (684)
10,000	20 (26,938)	19 (18,962)	18 (12,789)	18 (3554)	17 (1561)	17 (1098)	16 (903)	15 (755)	15 (690)

Variation trends for T^* under different initial planting densities but with the same discount rate were inconsistent. Table 4 shows that when the discount rate was 0.09, initial planting densities had a steady increasing effect on T^* . However, at lower discount rates, T^* first decreased and subsequently increased, indicating a change in the effect of the initial planting density on the optimal economic rotation, from negative to positive. The difference in the growth rate of standing timber volume and the discount rate ($\Sigma Q_T^j / \Sigma Q^j - r$) determined the direction of the effect of the initial planting density on the rotation period. A relatively high discount rate ($r = 0.09$) that exceeded the growth rate of the standing timber volume in the Chinese fir plantations at any stand age was associated with a negative value of $\Sigma Q_T^j / \Sigma Q^j - r$. Applying Equation (8), because of the positive value of dT/dm , a higher initial planting density corresponding to a longer optimal economic rotation period was obtained. As Figure 1 shows, relatively low discount rates intersected with the growth rates of standing timber volume in the Chinese fir plantations at different initial planting densities. During the early growth stage of Chinese fir, the growth rate of the standing timber volume was higher than the discount rate. A positive value for $\Sigma Q_T^j / \Sigma Q^j - r$ corresponded to a negative value for dT/dm . Conversely, a decline in the growth rate of the standing timber volume of Chinese fir in the plantation resulted in a negative value for $\Sigma Q_T^j / \Sigma Q^j - r$ and a positive value for dT/dm . Moreover, at lower initial planting densities, T^* was more sensitive to the discount rate. At the lowest initial planting density (1667 seedlings/ha), when the discount rate increased from 0.01 to 0.09, T^* decreased by 8 years. At the highest initial planting density (10,000 seedlings/ha), there was only a 5-year reduction in T^* . These differences in the values of T^* were not solely attributable to variations in discount rates; differences in the stumpage prices also played an important role, which is discussed in the following section.

5. Discussion

The optimal economic rotations obtained by calculating *LEV*s under different initial planting densities of Chinese fir showed that for the lowest initial planting density, the highest *LEV* was obtained under the condition of a constant discount rate. In a study conducted on Scots pine, Gong recommended a low initial planting density (670 seedlings/ha), which was considerably lower than the legal requirement of 1300 seedlings/ha [18]. Lohmander also recommended a very low economically optimal plantation investment, which implies a low initial planting density. Moreover, he recommended that the competent authority should relax the stipulation on the afforestation density level [46]. In another study on Chinese fir plantations, focusing on optimal economic rotation through stand density control, Xu et al. suggested that, ideally, the initial planting density should range between 2200 seedlings/ha and 3300 seedlings/ha [13]. Therefore, a low initial planting density generates the highest *LEV* for Chinese fir plantations, given the assumptions in this analysis. Although a low initial planting density appears to be reasonable from the standpoint of the *LEV*, the most suitable low planting density should be at least as low as that proposed in this paper, which reflects a situation that remains unclear and should be determined according to the stand growth dynamics of Chinese fir plantations.

These results further show that the T^* s of stands with the highest and lowest initial planting densities were both long. Consequently, some experts on forest management, for example, Coodres, have posited that planting densities and T^* are irrelevant and that only the planting density affects profits generated from timber production profit [14]. In light of the results shown in Table 4, we suggest that changes in the discount rate may account for this contradictory result. Coodres' conclusion is based on his use of a discount rate of 0.04 [14] and is therefore consistent with our results for a discount rate of 0.05. However, an increase in the discount rate corresponded to a higher initial plant density and an increased length of T^* . Therefore, the discount rate is a key factor determining the relationship between the initial planting density and T^* . For example, Solberg and Haight recommended an initial planting density of 2700 seedlings/ha for Norwegian spruce, without thinning, at a low discount rate and 950 seedlings/ha at a high discount rate [24].

Equation (8) expresses the impact of the discount rate on the relationship between the initial planting density and T^* . Some forestry scholars, for example, Xu et al., have argued that the initial planting density of Chinese fir has no connection with the discount rate [13]. This is because the values of T^* for different initial planting densities calculated by Xu et al. all exceeded 20 years, at which point the growth rates of standing timber volume were asymptotically equal to 0. If T^* s coincided with higher growth rates of standing timber volume, then the discount rate would certainly influence the determination of the relationship between the initial planting density and T^* .

As Figure 2 shows, the growth rate of Chinese fir in our experimental plantation rose during the early growth stage and then decreased sharply, approaching zero in relation to the stand age. The absolute value of $\Sigma Q_T^j / \Sigma Q^j - r$ was small, which mainly determined the direction of the impact of the initial planting density on T^* . The extent of the impact of the initial planting density on T^* mainly depended on the effect of the stand density on the stumpage value, $\partial \Sigma p^j Q^j / \partial m$ (see Equation (8)). The stumpage value of a stand was calculated as the sum of the timber volume of diameter class j multiplied by the net stumpage price, p_j . When attempting to determine the most suitable initial planting density, some scholars have considered the price differences of diameter classes [14,18,47]. Gong suggested that the most important factor affecting the optimum initial planting density and *LEV* was the short-term variation of stumpage prices [18]. Chen also pointed out that the price difference of diameter classes was a key consideration in the calculation of the optimal economic rotation period. If the price of large-sized timber does not differ markedly from the prices of medium-sized and small-sized timber, then the optimal economic rotation length would be shortened [11]. In addition, T^* is influenced by the different final harvesting costs attributed to stand density effects. A higher proportion of large-sized timber corresponds to a lower final harvesting cost and, conversely, a lower proportion of small-sized timber corresponds to a higher final harvesting cost. The length of the optimal economic rotation is reduced if the average final harvesting cost is used for its calculation [11]. Therefore, a combination of the price and cost effects accentuates the net price differences for different initial planting densities, which is the crucial determinant of the extent of the impact of the initial planting density on T^* .

6. Conclusions

We explicitly included the distribution of stand diameter classes and timber price differences representing the quality of stumpage in our model of forest *LEV*. We then used data observed for five initial planting densities of Chinese fir in an experimental plantation over a period of 35 years to compare the *LEVs* associated with these densities and explored optimal rotations under different discount rates. The results of the analysis revealed that there were two critical and uncertain factors that could affect the relationship between the initial planting density of Chinese fir and the optimal economic rotation period. The first was the difference in the values of the growth rate of the standing timber volume of a stand and the discount rate at that time. The second was the quality effect relating to the initial planting density. When the growth rate of the standing volume was higher than the discount rate, the initial planting density had a negative impact on the optimal economic rotation period. In the reverse case, the impact was positive. Thus, when very slow-growing species were selected for planting, the relationship between the optimal economic rotation period and the initial planting density was positive. Moreover, the quality effect could result in greater sensitivity of the optimal economic rotation period to variations in the initial planting density. Our findings on standing timber volume showed that with an increase in the stand age, the proportion of large-sized timber in stands where the initial planting was of lower density increased at a faster pace than those in stands where the initial planting was of higher density. The corresponding price difference could lead to significant differences in *LEVs* for different initial planting densities. In conclusion, we favor low-density Chinese fir plantations from the standpoint of obtaining the highest *LEV*. However, further research on optimum initial planting densities is required to explore this issue more fully.

The findings of this study have revealed the impact of initial planting densities on optimal economic rotation periods based on certain assumptions. When the discount rate was low, the optimal economic rotation lengths for the varying initial planting densities exhibited minimal differences. However, *LEVs* increased with increasing planting density, that is, the low cost of planting production and the high profitability of timber production converged in low-density forest plantations. When the discount rate was higher, a lower initial planting density corresponded to a shorter rotation period, implying a faster turnover of the investment and a low optional risk. Optimal economic rotation lengths were shortest for an initial plantation density of 3000–5000 seedlings/ha when the discount rate was at a median value, resulting in the fastest turnover of the investment.

The issue is more complex and managers minimally require further information on the stand density-driven production function and the economic environment, including price changes and regeneration costs, to enable them to manage Chinese fir in plantations efficiently. As a future research direction, forest economists should focus on determining the productive function, given its importance for analyzing economic phenomena.

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