Research paper

Estimation of the Stand Carrying Capacity of Chinese Fir Plantations In Taiwan

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【Summary】

Forest stand dynamics is the process of stand structural changes through time, which is a function of species, site quality, climate, stand age, and management treatments. Assessing competition behaviors is important to predict stand growth and yield and to prescribe appropriate silvicultural treatments. Chinese fir (*Cunninghamia lanceolata* Hook), an important commercial species in southern China, was imported to Taiwan in the early 20th century. Since stand productivity has considerably declined with successive short rotations, it was suggested that the length of rotations be extended. However, the potential growth and yield of older Chinese fir plantations have not been explicitly explored in the forestry literature. Therefore, in this study, we evaluated the stand dynamics of Chinese fir plantations established over 60 yrs . Data were collected from 30 Chinese fir stands in central Taiwan and from inventory records published in the past few decades, which provide a sound basis for analyzing long-term stand carrying capacity and competition behaviors. Results indicated that competition behaviors were similar between Taiwan and southern China, but tree mortality levels in Taiwan were lower than those in southern China for a given tree size. The difference may have been due to higher winter temperatures in Taiwan. At age 18 , the maximum stand basal area of 56.52 m^2 ha^{-1} estimated for Chinese fir is close to that for loblolly pine at the same age planted in the southeastern US. However, stand basal area among stands varied. In addition, we suggest that the impacts of unpredictable natural disturbances, such as typhoons, on stand dynamics and stand structure need to be assessed. Results of this study can provide insightful information about long-term stand dynamics for Chinese fir and useful guidance for forest resource managers in designing forest management practices.

Key words: old-growth stand, competition, self-thinning, *Cunninghamia lanceolata*, growth and yield.

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研究報告

臺灣杉木人工林林分承載量的估測

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摘　要

林分的動態改變受到物種組成、立地條件、氣候、林齡與撫育方法等不同因子的交錯影響。林木競爭的評估是預測林分生長收穫與制定育林措施的重要指標。杉木(*Cunninghamia lanceolata* Hook) 作為中國南方重要的人工林經濟樹種，於二十世紀初葉引進臺灣栽植。現有的連續短輪伐期森林經營方式，造成林分產出量的大幅下降。有鑑於此，許多文獻建議將原有的杉木人工林輪伐期延長。然而，過去對於杉木長期生長與收穫的研究尚顯不足(大於三十年生的林分)。因此，本研究將探討杉木人工林長時間的林分動態改變。研究資料來自於中臺灣30座杉木人工林長期監測資料和過去研究文獻發表的杉木人工林資源調查資料，提供了研究杉木長期生長收穫與林分承載量的重要基礎。本研究結果顯示，杉木人工林在中國南方與臺灣的競爭表現相似，但是臺灣杉木的死亡率較中國南方低，此差異或許導因於臺灣冬季的氣溫較高。18年生的臺灣杉木林分，林分胸高斷面積承載量可達56.52 m^2 ha^{-1}和美國南方松相同林齡的林分承載量相近，但臺灣杉木林分間的差異仍大。此外，自然災害(如：風害)造成林分動態與結構的改變，為長輪伐期的杉木人工林經營須考量的影響因子。希望本研究的成果能提供長期杉木生長研究與人工林經營方法擬定的參考依據。

關鍵詞：老齡林、林木競爭、自我疏伐、杉木、生長收穫。

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INTRODUCTION

Forest stand dynamics is process of stand structural changes through time, which is a function of species, site quality, climate, stand age, and management treatments (Oliver and Larson 1996). When site resources no longer adequately support additional growth of all present trees, mortality occurs, which results in a decreasing number of trees per unit area (i.e., self-thinning) (Burkhart and Tomé 2012). Assessing the extent of competition and self-thinning relationships is important for predicting stand growth and yield and prescribing appropriate silvicultural treatments (e.g., thinning) (Burkhart and Tomé 2012). In practice, size-density relationships and stand basal area-age relationships are 2 commonly used quantitative approaches. The former focuses on the relationship between the size of the average tree and the number of trees per unit area in a stand; the latter focuses on the total amount of yield over a period of time in a stand (Yang and Burkhart 2017). Stand basal area incorporated with size information (i.e., the size-density relationship) is a useful and improved quantification for prescribing silvicultural treatments and projecting stand growth and yield (Burkhart and Tomé 2012).

Chinese fir (*Cunninghamia lanceolata* Hook), also known as China-fir, is a fast-growing coniferous tree species native to tropical and subtropical China. With its highly durable and valuable wood, Chinese fir has been widely planted as a commercial species for timber production in southern China over hundreds of years (Li and Ritchie 1999). In the early 20th century, Chinese fir was primarily imported from Fujian Province, China into Taiwan and extensively planted in mountainous regions of central and southern Taiwan at 500~1800 m in elevation (Hung 1969, Jen 1994). During 1971 to 1980, Chinese fir comprised more than 60% of total conifer timber production in Taiwan (Liu 1982).

Generally, Chinese fir is harvested at ages of 20~25 yrs by clear-cutting; however, with increasing demands for wood supply, the rotation age was shortened by 5 yrs or even more in southern China (Bi et al. 2007). In Taiwan, the final harvest of Chinese fir is commonly conducted at younger ages, of about 14~20 yrs (Hung 1969). With successive short rotations, it was reported that stand productivity has considerably declined due to depletion of soil nutrients (Bi et al. 2007). Therefore, it was suggested that the length for the second rotation should be extended to around 30 yrs (Tian et al. 2011, Selvaraj et al. 2017). As pointed out by Miao et al. (2019), the soil status was found to be better in 45-yr-old stands than in 25-yr-old stands, in terms of soil physicochemical properties, microbial community composition, and enzyme activities. By examining more than 50 research studies of Chinese fir published in Taiwan and China in the past, it was reported that most studies focused on relatively young plantations (< 30^{yr} old) (Kao 2013). Kao (2013) found that the long-term growth and yield of Chinese fir can be well estimated by the Schnute growth model based on R^2 and the root mean square error. However, the potential of the stand carrying capacity and competition behaviors of older Chinese fir plantations have not been explicitly explored in the forestry literature. In central Taiwan, Chinese fir plantations aged 30~60 yrs still remain as a part of the National Taiwan University Experimental Forest and Taiwan Forestry Bureau, which provide a sound basis for analysis.

Therefore, the main objective of this study was to evaluate competition behaviors and the stand carrying capacity of Chinese fir plantations established over 60 yrs using data collected from 30 Chinese fir stands across central Taiwan. To provide a comprehensive view of Chinese fir plantations in Taiwan, we also examined inventory records published in research papers and reports in the past few decades. Size-density relationships and basal area-age relationships were estimated and compared with other studies. Results of this study should enhance understanding of plant competition, forest stand dynamics, and stand productivity for old-growth Chinese fir. In addition, this study can provide guidance for forest resource managers when making decisions on planting density, thinning schedules, and rotation ages for Chinese fir plantations.

MATERIALS AND METHODS

In this study, 2 sources of data were collected: one from 30 Chinese fir stands in central Taiwan and the other one from inventory records published in research papers and reports. Stand level information (e.g., stand basal area, number of trees per hectare, and quadratic mean diameter) from the 2 sources of data were combined to estimate size-density relationships and stand basal area-age relationships.

Data collected from 30 Chinese fir stands

Thirty Chinese fir stands in central Taiwan were selected with stand ages ranging 26~60 yrs and at elevations of 726~1490 m above sea level. Twenty-three of 30 stands were located in 3 districts of the National Taiwan University Experimental Forest, including Shuili, Neimaopu, and Heshe. The remaining 7 stands were located in 3 districts, also known as working circles, of the Forestry Bureau: Mt. Pa-hsien, Choshui River, and Puli. Annual mean temperature ranges 20~23 ℃, and annual mean precipitation is about 2000 mm yr^{-1} (National Taiwan University Experimental Forest 2019). The initial planting densities ranged 2000~3884 trees ha^{-1}.

In total, 138 square temporary plots of 0.01 ha in size were established among the 30 stands (i.e., 4 or 5 plots per stand on average) in 2012~2013. No remeasurements were taken after 2012~2013. The stands selected for plot installation were representative of management and silviculture practices for Chinese fir in Taiwan. The diameter at breast height (DBH) was recorded to the nearest 0.1 cm, and the total tree height was measured to the nearest 0.1 m. The stand basal area (m^2 ha^{-1}), number of trees per hectare, and quadratic mean diameter (cm) were calculated. Summary statistics of stand characteristics across 6 regions are given in Table 1.

Inventory records published in research papers and reports

Ninety inventory records of Chinese fir plantations were collected from 15 research papers published in Taiwan (Sato 1941, Liu 1950, 1982, Hung 1953, 1969, 1970, Lin 1954, 1956, Jheng 1958, Liu et al. 1965, Chen 1968, 2007, Horng et al. 1985, Gao et al. 1986, Huang and Sun 1986), National Taiwan University Experimental Forest reports, and the 3rd national forest inventory database from the Taiwan Forestry Bureau. Research papers we collected were mainly published by the Taiwan Forestry Research Institute and National Chung-Hsing University Experimental Forest, which focused on the growth and yields of relatively young Chinese fir plantations (i.e., aged ≤ 30 yrs). Stand-level information, including the stand age, stand basal area (m^2 ha^{-1}), and number of trees per hectare, provided in the published research papers and reports were included in the analysis. The quadratic mean diameter (cm) was calculated using the number of trees per hectare and stand basal area (m^2 ha^{-1}).

Estimation of size-density relationships

1. Size-density relationship expressed on a log-log scale

   In general, there are 2 stages in the size-density trajectory on a log-log scale: stage I is the density-independent mortality stage, and stage II is the competition-induced (self-thinning) mortality stage (VanderSchaaf and Burkhart 2008). A stand progresses from

Table 1. Summary statistics for Chinese fir stand characteristics among 30 stands across 6 regions in central Taiwan. TPH_{intl}, average initial planting density (trees ha^{-1}); Avg. DBH (cm), average diameter at breast height; Avg. Ht (m), average total tree height of live trees in the plantations; Avg. TPH, average number of live trees per hectare. Standard deviations for DBH, Ht, and TPH are given in parentheses

Region	Elevation (m)	Age (yr)	Avg. THP_{intl}	Avg. DBH	Avg. Ht	Avg. TPH
Shuili	905~991	26~33	2282	26.4 (2.5)	18.0 (1.6)	1475 (222)
Neimaopu	692~1276	32~54	3098	29.7 (7.2)	17.4 (2.9)	921 (221)
Heshe	857~1360	31~58	2353	24.8 (4.7)	15.4 (1.8)	1236 (443)
Mt. Pa-hsien	909~1008	54~56	2663	28.6 (4.6)	17.2 (2.1)	854 (282)
Choshui River	875~1012	39~40	2250	26.1 (4.2)	16.0 (2.7)	925 (243)
Puli	909~1490	49~60	3300	28.1(7.9)	16.1 (3.2)	765 (353)

stage I to stage II because of the occurrence of competition. The maximum size-density relationship (MSDR) is a boundary or maximum "trade-off" between the number of trees per unit area and the average tree size that can be sustained in a given stand. Reineke (1933) found in fully stocked even-aged plantations, the maximum stand density and quadratic mean diameter follow a linear relationship on a log-log scale:

$$\mathrm{LnN} = \mathrm{Lna} + \mathrm{b} \times \mathrm{Ln}\overline{\mathrm{D}}_{\mathrm{q}}; \qquad (1)$$

where Ln is the natural logarithm, N is the number of trees ha^{-1}, $\overline{D}_q$ is the quadratic mean diameter (cm), and a and b are coefficients. Reineke (1933) indicated that the slope (b), close to -1.605, is generally consistent among species and locations but the value of the intercept (a) varies.

2. Size-density relationships expressed as a unitless measure

Relative spacing (Hart 1926) is defined as the ratio of the average distance between trees in meters divided by the average dominant tree height (m) of a stand, which is a unitless measure to describe the size-density relationship. For even-aged stands, the relative spacing rapidly decreases with increasing stand age and then approaches a lower limit. The lower limit can be referred to as a self-thinning line. Diameter-based relative spacing (RSD) is an alternate formulation of relative spacing by replacing the average dominant tree height with the quadratic mean diameter, as suggested by Yang and Burkhart (2018). RSD can be expressed as a function of stand age:

$$\mathrm{RSD} = \frac{\sqrt{\frac{10,000}{\mathrm{N}}}}{\overline{\mathrm{D}}_{\mathrm{q}}} = f(\mathrm{A}); \qquad (2)$$

where N is the number of trees per hectare, $\overline{D}_q$ is the quadratic mean diameter (cm), and A is the stand age (yr).

The stand age function is specified in Yang and Burkhart (2018) as:

$$f(\mathrm{A}) = c_1 \times ec^{2 \times A^{c_3}}; \qquad (3)$$

where c_1, c_2, and c_3 are coefficients.

regression (quantile = 0.90), and those for RSD were estimated by a nonlinear quantile regression (quantile = 0.10) in R.

Estimation of stand basal area-age relationships

The stand basal area, the sum of cross-sectional areas of all stems at breast height in a unit area (m^2 ha^{-1}), is an informative expression of stand density levels. The maximum stand basal area that is sustainable over a period of time can be regarded as a measure for determining the carrying capacity of a stand [and/or?] the site potential limitations on stockability (Burkhart and Tomé 2012). As indicated by Yang and Burkhart (2018), RSD is advantageous for calculating the basal area stand carrying capacity by squaring both sides of Equation 1 and multiplying by the constant c (approximately 0.00007584); that is,

$$RSD^2 \times c = \left[\frac{\sqrt{\frac{10,000}{\mathrm{N}}}}{\overline{\mathrm{D}}_{\mathrm{q}}}\right]^2 \times c = [f(\mathrm{A})]^2 \times c; \qquad (4)$$

The stand basal area (G) can be estimated by rearranging the above equation:

$$\mathrm{G} = \frac{10000 \times c}{[f(\mathrm{A})]^2}; \qquad (5)$$

RESULTS

As shown in Fig. 1A, the number of trees per hectare began to decline as the quadratic mean diameter approached around 15~20 cm (i.e., $Ln(\overline{D}_q)$= 2.7~3.0). Stands diverged from the self-thinning line with increasing tree size and stand age (Fig. 1B). Notably, the stand density for some stands decreased below 1000 trees ha-1 (i.e., $Ln(N)$= 6.9) after 30 yr or with a quadratic mean diameter of > 20 cm (i.e., $Ln(\overline{D}_q)$= 3.0). In this study, the slope (b) and intercept (a) of the self-thinning line were -1.14 (95% confidence interval (CI): -1.23~-1.06) and 11.12 (95% CI: 10.89~11.39), respectively. The estimated slope statistically differed from that proposed by Reineke (1933). As shown in Figure 1B, RSD decreased to a lower limit of 0.075 (i.e., the self-thinning line) with an increasing stand age. Around the ages of 30~40 yrs, an RSD of > 0.25 was found for 2 stands, whose stand density were appreciably lower than the majority (of < 600 trees ha^{-1}) (Fig. 1B).

In general, the stand basal area increased as the stand age increased. The growth rate decreased with stand development. In this study, about 10% of the stands could carry more than 80 m^2 basal area ha^{-1} around an age of 60 yr (Fig. 1). Notably, a maximum stand basal area of 56.52 (m^2 ha^{-1}) was estimated at 18 yr of age. However, as shown in Fig. 1, the variation in the stand basal area among stands was high, ranging 37~88 (m^2 ha^{-1}) at age 60 .

DISCUSSION

In this study, the slope (b) and intercept (a) were -1.14 (95% CI: -1.23~-1.06) and 11.12 (95% CI: 10.89~11.39), respectively. To compare size-density relationships among various stands, Reineke (1933) proposed a stand density index (SDI), which was defined as the limiting number of trees when the quadratic mean diameter was equal to 25.4 cm. Based on the coefficients estimated, the SDI of 1690 trees ha^{-1} was calculated for Chinese fir plantations in this study. Chiu et al. (2018) reported that the respective self-thinning equations for 32-yr-old Formosan cypress (*Chamaecyparis formosensis*) and Taiwan cypress *(Chamaecyparis obtusa* var. *formosana*) plantations were

$$Log\overline{D}_q = 3.379 - 0.662 \times Log N \text{............ (6)}$$

and

$$Log\overline{D}_q = 3.669 - 0.801 \times Log N \text{............ (7)}$$

where Log is the base 10 logarithm. The SDIs for the 2 species were estimated to be 960 and 671 trees ha-1, which were lower than that for Chinese fir found in this study. In addition, Chiu (2015) reported the self-thinning line estimated for 70-yr-old Taiwania (*Taiwania cryptomerioides*) plantations in southern Taiwan was

$$Log N = 5.429 - 1.615 \times Log\overline{D}_q = \text{......... (6)}$$

The SDI of 1446 trees ha-1 for Taiwania is lower than that for Chinese fir.

Similar to Chinese fir, loblolly pine is a fast-growing and commercially important species in the southeastern US. Notably, the general trend of the RSD-age curve for Chinese fir was similar to those for loblolly pine found by Yang and Burkhart (2018). However, it took over 60 yr for Chinese fir stands to reach the lower asymptote, which is longer than loblolly pine stands. It was close to that of 59.19 m2 ha-1 at the same age for loblolly pine in the southeastern US (Yang and Burkhart 2018). This implies that Chinese fir in Taiwan has potential to yield at a similar stocking level to younger-aged loblolly pine plantations.

As reported by Zhang et al. (2016), the slope coefficient of -2.45 in Guangxi, Jiangxi, and Fujian Provinces, China was closer to the estimate found in this study than that of -4.22 in Sichuan Province, China, which may have been due to the similarity of climatic conditions between Taiwan and southern China (i.e., Guangxi, Jiangxi, and Fujian Provinces). It was indicated that self-thinning trajectories for Chinese fir plantations are nearly consistent across different initial planting densities; however, the

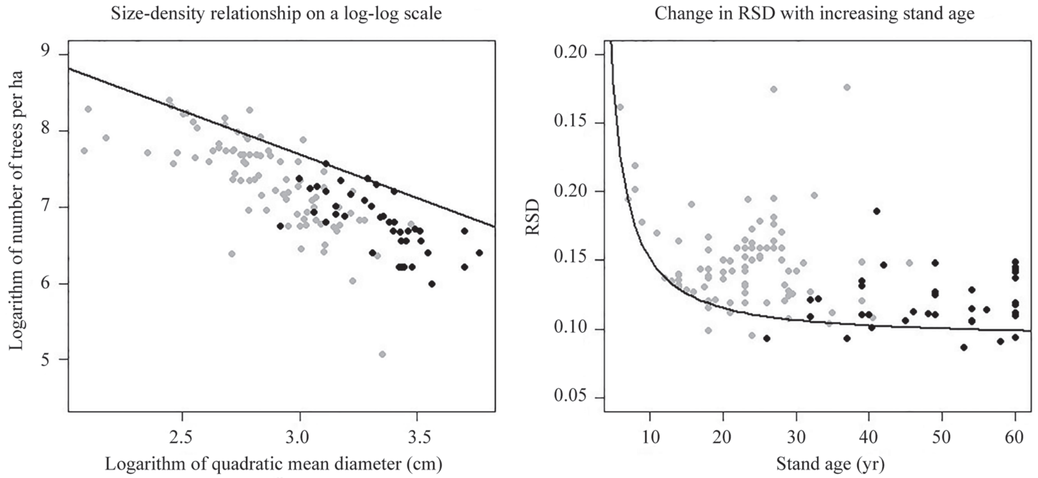

Fig. 1. Size-density relationships for Chinese fir plantations in Taiwan. Solid black dots represent observations collected from 30 Chinese fir stands, while solid gray dots represent observations collected from inventory records published in research papers and reports. In total, data on 90 stands were collected. (A) Relationship between the quadratic mean diameter and number of trees per unit area on a log-log scale. The solid black line illustrates the limiting relationship between the 2 variables. (B) Changes in the diameter-based relative spacing index with increasing stand age. The solid black curve describes the lower limit of self-thinning.

slopes of self-thinning lines vary among physiographic regions (Zhang et al. 2016).

Although the competition behaviors are similar between Taiwan and southern China, tree mortality levels in Taiwan were lower than those in southern China for given tree size (i.e., there was a flatter self-thinning line). The difference may have resulted from higher temperatures in winter in Taiwan. Zhang et al. (2018) indicated that self-thinning trajectories for Chinese fir are sensitive to climate, specifically the winter mean minimum temperature (WMMT). The WMMT in central Taiwan ranges 15~18℃; however, WMMTs of 4.58, 4.42, and 11.96℃ were recorded in Fujian, Jiangxi, and Guangxi Provinces, respectively (Zhang et al. 2018).

In this study, natural stump sprouting was found in some older stands, resulting in considerably high stand basal areas (> 80 m^2 ha^{-1}) (Fig. 1). In addition to providing timber production, Chinese fir plantations are also important habitats for various species. Eighty-five understory plant species were recorded in a 56-yr-old Chinese fir plantation in Fujian Province (Lin et al. 1999). Therefore, how to implement appropriate silvicultural treatments for desired objectives on specific sites needs to be addressed.

In Taiwan, more than 70% of annual rainfall is brought by typhoons during late summer and early fall. Heavy rainfall on rugged, dense mountains with strong winds leads to severe damage to forests and economic losses every year (Liu 1957). In 1969, catastrophic wind damage to Chinese fir plantations resulted in greater than a 19% mortality rate, especially among young plantations (Chen and Chen 1972). Thus, assessing the impacts of unpredictable natural disturbances on stand dynamics and stand structure is necessary to suggest proper management strate-

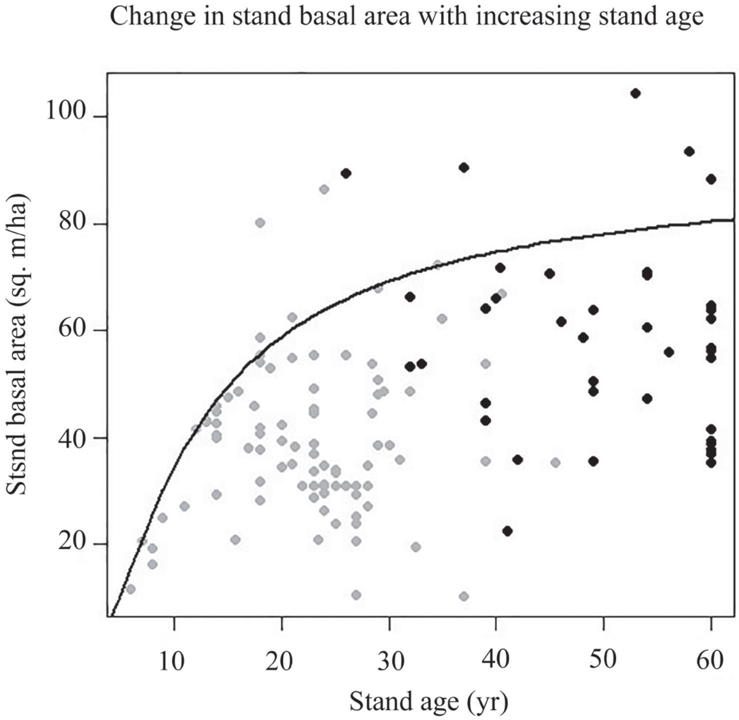

Fig. 2. Depiction of changes in the stand basal area over time for Chinese fir plantations in Taiwan. Solid black dots represent observations collected from 30 Chinese fir stands, while solid gray dots represent observations collected from inventory records published in research papers and reports. In total, data of 90 stands were collected. The solid black curve is the stand basal area carrying capacity implied by diameter-based relative spacing (RSD).

gies and silvicultural treatments for long-term rotations of Chinese fir plantations.

Indeed, the data used in analyses were collected neither from a single designed experiment nor from permanent plots for a particular research objective. However, the stands were representative of climatic conditions and management practices for Chinese fir in Taiwan. The general trend of long-term stand dynamics for Chinese fir shown in this study will provide useful information for forest managers when designing forest management practices.

CONCLUSIONS

In summary, the stands diverged from the self-thinning line with increasing tree size and stand age. Stand density for some stands decreased below 1000 trees ha-1 after 30 yr or with a quadratic mean diameter of >20 cm. The SDIs for Formosan cypress and Taiwan cypress were estimated to be 960 and 671, which were lower than that of Chinese fir found in this study. The self-thinning line for Chinese fir plantations in Taiwan is similar to that in southern China; however, tree mortality levels in Taiwan were lower, which may have been due to higher mean winter temperatures.

In general, the stand basal area increased as the stand age increased. About 10% of the stands can carry more than 80 m^2 basal area ha^{-1} at around 60 yrs of age. At age 18 , the maximum stand basal area of 56.52 m^2 ha^{-1}

was estimated. However, stand basal areas among stands considerably varied. In addition, the impacts of unpredictable natural disturbances, such as typhoons, on stand dynamics and stand structure should be assessed. Results of this study can provide insightful information about long-term stand dynamics for Chinese fir and useful guidance for forest resource managers when designing forest practices.

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