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The Carbon Benefit of Thinned Wood for Bioenergy in Taiwan

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Abstract: Forest thinning is a way to make room for the growth of remaining trees, and the thinned wood can serve as a fuel for bioenergy in order to combat climate change. Using thinned wood for bioenergy can substitute for fossil fuel energy, resulting in potential carbon benefit. Since not all thinned wood can be transported out of the forest for processing, the extraction ratio (extraction volume/thinning volume) is an important variable for determining the net carbon benefit. This study investigated 52 forest-thinning sites in Taiwan. The extraction ratio was estimated to explore the benefit of thinned wood used as bioenergy. Cross analysis was adopted to find the relationships between site/species attributes and extraction ratio. The factors included age class, thinning method, land use classification, and species. Key variables included thinning volume, extraction volume, and extraction ratio. Statistical analysis was then applied to identify the significant differences. The analysis shows that the extraction ratio of thinned wood is 57.12%. The research outcomes could provide valuable information for green-energy policy making in Taiwan.

Keywords: carbon benefit; forest thinning; bioenergy; cross analysis; ANOVA; Duncan's MRT

1. Introduction

Climate change resulting from the increase in atmospheric greenhouse gases has become a prominent topic worldwide [1]. Replacing fossil-fuel-based electrical generation with renewable energy sources (e.g., wind, solar, and biomass) is a critical step in slowing global warming. Currently, however, less than 5% of the electricity is generated by renewable energy in Taiwan, which is much lower than the ratio (13%) of renewable energy worldwide. According to Kyoto Protocol article 3.4 [2], forest management can be used to increase carbon storage. Of Taiwan's renewable energy, 27.4% of the electricity stems from bioenergy. Through photosynthesis, forests absorb and fix carbon dioxide from the atmosphere, thereby acting as atmospheric carbon dioxide sinks. Forest thinning is a forest management strategy for improving the timber quality of the selected trees and achieving sustainability of forests [3–5]. Forest thinning also has a potential carbon benefit. Wood from forest thinning can serve as a fuel for bioenergy since using thinned wood for bioenergy can substitute for fossil fuel energy, instead of leaving the thinned wood in the forest to decay. In Japan, Etoh et al. [6] concluded that if the wood waste from thinned logs had been used to generate bioenergy, its annual carbon substitution capacity would have been the equivalent of 37.8–62.6 million tons of carbon dioxide.

However, for a variety of operational and economic reasons, not all thinned wood in Taiwanese forests is transported out of the forest for processing. This ratio between wood transported out of the forest relative to the total wood harvested in thinning is termed the extraction ratio. It is an important variable for determining the net carbon benefit that can be derived from using thinned wood for bioenergy since it reflects how much of the thinned logs have been actually used for bioenergy. Understanding how extraction ratio varies with stand age, thinning method, and other conditions would be useful for designing management regimes which increase the carbon benefits of using thinned wood for bioenergy.

Several factors regarding carbon benefits from forest thinning have been explored. According to the study in [7], moderate thinning was the most effective option (reduction of 553.59 kg/ha of carbon dioxide per NT $1000), followed by light thinning (551.75 kg/ha per NT $1000), and then heavy thinning (521.08 kg/ha per NT $1000) in terms of cost-effectiveness. Note that 30 New Taiwan Dollars (NT $) $\approx$ 1 United State dollar. In a thinning project for conifer plantations in the forest management zone of Da-an Shi Working Circle, Yen et al. [8] concluded that, from an economic perspective, heavy thinning was ideal for Taiwan red cypress (*Chamaecyparis formosensis*), Taiwan yellow cedar (*C. taiwanensis*), Taiwania (*Taiwania cryptomerioides*), and dragon spruce (*Picea asperata*), whereas clear cutting was ideal for China fir (*Cunninghamia lanceolata*) and Japanese cedar (*C. japonica*.) The moderate thinning was deemed the most appropriate strategy for *C. formosensis*, *C. taiwanensis*, *T. cryptomerioides*, and *P. asperata* when they were not at rotation age, whereas clear cutting was ideal for *C. lanceolata* and *C. japonica*. Simulations on *P. sitchensis* plantations by Dewar and Cannell [9] revealed that thinning can reduce the amount of forest carbon by 15%. Vesterdal et al. [10] investigated the carbon accumulation of Norway spruce (*P. abies*) and found that carbon accumulation exhibited a negative linear correlation with thinning intensity, which was subsequently confirmed by Nilsen and Strand [11].

This work presents the variability of thinning treatments in managed forests in Taiwan. The aim of this study is to estimate the extraction ratio in order to explore the benefits of employing a bioenergy for mitigating climate change. In this study, important data regarding extraction volume, extraction ratios, and thinning treatments of the thinning sites were collected and analyzed. The key variables associated with forest thinning were fully explored to identify their connections, and statistical analysis was applied to identify the significance.

2. Methodology

Thinning is a way to make room for the growth of trees by removing some trees or parts of trees. Extraction is the process that transports thinned logs from the place where it grew to another place where it can be removed from the site. This study explores the carbon benefit of thinned logs that are used for bioenergy. The extraction ratio is used as an indicator to evaluate the impact on climate change. Table 1 shows the attributes of the research sites, collected by several Forest District Offices of the Forestry Bureau of Taiwan during 2003 to 2012 [12]. The land use can be categorized into timber management area (LC1), national protected area (LC2), and forest recreation area (LC3). The age class includes the following bins: 1–20 years (AC1), 21–30 years (AC2), 31–40 years (AC3), 41–50 years (AC4), 51–60 years (AC5), and over 60 years (AC6). The thinning method is characterized by three-row clear cutting, eight-row thinning (TT1), low thinning (TT2), cleaning (TT3), intermediate/low thinning (TT4), gap thinning (TT5), rows (TT6), and selective cutting (TT7). Note that LC1-LC3, AC1-AC6, and TT1-TT7 are labels defined by the authorities. The main tree species for certain site are selected based on the number of trees per area. Statistical analysis methods, including cross analysis, analysis of variance (ANOVA), and Duncan's multiple range test (MRT), were used to find the relationships between the key thinning factors and to identify the thinning benefits under different conditions. The explored site/species attributes include age class, thinning method, land use classification, and species. The thinning factors that are taken into consideration include thinning volume, extraction volume, and extraction ratio.

This study assessed the carbon benefits of various thinning treatments in Taiwan. Forest carbon content can be estimated by calculating the forest biomass from the tree volume and wood density. The tree volume is determined by a national formula [13] in Taiwan. Both diameter (D, unit: cm) and tree height (H, unit: m) are needed for estimating the tree volume (V, unit: m^3). The formula differs from tree species, as shown in Table 2.

Table 1. Attributes of research sites.

Item	Classification	Number of Records	Percentage (%)
Land use classification	LC1 (Timber management area)	42	66.7
	LC2 (National protected area)	11	17.5
	LC3 (Forest recreation area)	10	15.9
Altitude	<800 m	5	7.9
	801~1200 m	24	38.1
	1021~1600 m	21	33.3
	1601~2000 m	6	9.5
	>2000 m	7	11.1
Age class	AC1 (1–20 years)	4	6.3
	AC2 (21–30 years)	20	31.7
	AC3 (31–40 years)	23	36.5
	AC4 (41–50 years)	5	7.9
	AC5 (51–60 years)	8	12.7
	AC6 (>60 years)	3	4.8
Species	SP1	29	46.0
	SP2	8	12.7
	SP3	10	15.9
	SP4	7	11.1
	SP5	4	6.3
	SP6	5	7.9
Thinning method	TT1 (Three-row clear cutting, eight-row thinning)	6	9.5
	TT2 (Low thinning)	36	57.1
	TT3 (Cleaning)	7	11.1
	TT4 (Intermediate/low thinning)	3	4.8
	TT5 (Gap thinning)	1	1.6
	TT6 (Rows)	4	6.3
	TT7 (Selective cutting)	6	9.5

Note: SP1 = C. japonica or C. lanceolata, SP2 = C. lanceolata var. konishii or T. cryptomerioides, SP3 = C. japonica, C. lanceolate, and C. lanceolata var. konishii or T. cryptomerioides, SP4 = C. formosensis or C. formosana, SP5 = C. japonica or C. lanceolata and C. formosensis or C. formosana, SP6 = C. formosensis or C. formosana and C. lanceolata var. konishii or T. cryptomerioides.

Table 2. Tree volume estimation formulas with respect to diameter (D) and tree height (H) for different species.

Species	Tree Volume Estimation Formula (m^3)
C. japonica	$V = 0.0009015\ D^{1.9886} \times H^{0.6879}$
C. lanceolata	$V = 0.0000844\ D^{1.6790} \times H^{1.0655}$
C. lanceolata var. *konishii*	$V = 0.0000728\ D^{1.9449} \times H^{0.8002}$
T. cryptomerioides	$V = 0.0000944\ D^{1.9947} \times H^{0.6597}$
C. taiwanensis	$V = 0.0000944\ D^{1.9947} \times H^{0.6597}$
C. formosensis	$V = 0.0000944\ D^{1.9947} \times H^{0.6597}$
C. formosana	$V = 0.0000728\ D^{1.9449} \times H^{0.8002}$
Michelia formosana	$V = 0.0008626\ D^{1.8742} \times H^{0.8671}$
Zelkova serrata	$V = 0.0008626\ D^{1.8742} \times H^{0.8671}$

The carbon content of the thinned logs (C_{thin}) and the carbon content of the extracted logs (C_{rem}) are respectively calculated by

$$C_{thin} = V_{thin} \times BD \times BEF \times CF, \quad (1)$$

$$C_{rem} = V_{rem} \times BD \times CF \quad (2)$$

where V_{thin} denotes the thinning volume, *BD* is basic wood density, *BEF* represents the biomass expansion factor, *CF* is the carbon fraction, and V_{rem} represents the extracted volume, according to IPCC (2006) [14]. For the thinned logs, the stem biomass was obtained by the product of the thinning volume and the basic wood density. The aboveground biomass can be calculated by the stem biomass multiplied by an associated biomass expansion factor. The carbon content of the logs can be estimated by the aboveground biomass scaled by the carbon fraction of forest trees. For extracted logs, the stem biomass was obtained by the product of the extraction volume and basic wood density. The carbon content of extracted logs can be estimated by its stem biomass scaled by the carbon fraction.

The biomass expansion factors established by Wang and Liou [15] were adopted, and the values for coniferous trees and broadleaf trees were 1.23 and 1.20, respectively. The BD is defined as the ratio of the absolute dry weight of the stem and the cubic meter of the log under bark. The BD values used in this study were adopted from Lin et al. [16], who analyzed 24 coniferous and broadleaf tree species native to Taiwan. They reported that the BD of coniferous trees ranged between 0.31 and 0.55 (mean, 0.42), and the BD of broadleaf trees ranged between 0.37 and 0.77 (mean, 0.56). The CF of the native species was 0.4821 for coniferous trees and 0.4691 for broadleaf trees. The BD and CF values of species common for thinning operations are listed in Table 3.

Table 3. Basic wood density (BD) and carbon fraction (CF) values of species common for thinning operations.

Species	BD (ton/m^3)	CF
C. japonica	0.36	0.4903
C. lanceolata	0.31	0.4832
C. lanceolata var. *konishii*	0.32	0.4832
T. cryptomerioides	0.32	0.4832
C. taiwanensis	0.42	0.4822
C. formosensis	0.42	0.4864
C. formosana	0.54	0.4857
Michelia formosana	0.52	0.4751
Zelkova serrata	0.73	0.4821

Source: [17].

A cross-sectional study (also known as a cross analysis) is a type of observational study that analyzes data from a population, or a representative subset, at a specific point in time (i.e., cross-sectional data). We employed cross analysis to find the relationships between key variables related to forest thinning in order to identify the thinning benefits under various conditions. Site/species attributes (including age class, thinning method, land use classification, and species) were used to find the relationships between thinning related factors (including thinning volume, extraction volume, and extraction ratio). For thinning volume and extraction volume, normalized metrics (volume per hectare and volume per tree) were also investigated to provide more information.

One-way ANOVA was employed to identify any significant differences in the thinning volumes and extraction volumes between various species, age classes, thinning methods, and land use classifications. The results of ANOVA show if there exists a difference in the means of the variables. However, it cannot clearly indicate which means are different. Therefore, Duncan's new multiple range test (Duncan's MRT) was used as a post hoc test to measure specific differences between pairs of means. Any significant differences were subjected to Duncan's MRT as a post hoc test to verify the between-groups differences.

3. Results

3.1. Cross Analysis

Table 4 shows the variability of thinning intensities and extraction ratios of research sites. Thinning intensity varied greatly as well as extraction ratio. Site extraction volume at some sites was zero because in the case of cleaning cuts in the youngest stands, no logs were extracted. On the other hand, on sites with *C. formosensis* (i.e., SP4), the extraction ratio was even more than 100% because the site extraction volume was higher than the site thinning volume. It is noted that the extracted logs include previously thinned wood, leftovers from natural mortality, and windbreaks, which are usually already partially decomposed. The extracted wood can be made into wood pellets as bioenergy. Since most of extracted wood is from the newly thinned wood, it still has similar qualities in the context of bioenergy use.

Table 4. Thinning intensity, thinning volume, extraction volume, and extraction ratio of thinning sites.

Item	Number of Records	Minimum	Maximum	Mean	Standard Deviation
Thinned area per site (ha)	52	0.22	74.00	16.28	16.16
Number of felled trees per hectare	52	23	3000	412	379
Number of remaining trees per hectare	52	267	2237	991	398
Thinning intensity (%)	52	7.93	75.70	27.14	11.11
Site thinning volume (m^3)	52	41.63	3380.00	985.49	747.45
Thinning volume per hectare ($m^3 \cdot ha^{-1}$)	52	12.00	291.73	89.86	62.00
Thinning volume per tree (m^3)	52	0.03	1.11	0.26	0.20
Site extraction volume (m^3)	52	0.00 [1]	2462.36	539.11	523.09
Extraction volume per hectare ($m^3 \cdot ha^{-1}$)	52	0.00	248.85	48.59	47.00
Extraction volume per tree (m^3)	52	0.00	0.94	0.16	0.19
Extraction ratio (%)	52	0.00	107.72 [2]	57.12	30.99

Notes: [1]. Site extraction volume was zero because it was cleaning cutting and no logs were extracted. [2]. The species was *C. formosensis*, and the extraction ratio was more than 100% because the site thinning volume was less than the site extraction volume.

As shown in Table 5, extraction volume per hectare and extraction volume per tree increased with age, but the values declined in the class of >60 years. From Table 5, regarding the thinning methods, intermediate/low thinning yielded the highest site extraction volume (1012.52 m^3), although gap thinning yielded the highest extraction volume per hectare (123.82 $m^3 \cdot ha^{-1}$). Site extraction volumes of cleaning cutting were all zero because the method was mostly applied to unsuitable or undesirable trees with small diameters. In terms of land use classification, timber management areas (51.02 $m^3 \cdot ha^{-1}$) and national protected areas (69.23 $m^3 \cdot ha^{-1}$) yielded a higher extraction volume per hectare than did the forest recreation areas (15.64 $m^3 \cdot ha^{-1}$).

According to Table 6, the extraction ratio increased with the age class, culminating at the 41–50 years class (84.9%). Intermediate/low thinning had the highest extraction ratio (79.68%). Regarding the tree species, the extraction ratios of the groups were all relatively similar, with the highest ratio observed for the SP2 group (77.39%).

3.2. ANOVA Analysis

Table 7 shows that age class was of significance to the site extraction volumes and extraction carbon content per tree. Extraction volumes per tree increased with the age. In addition, the thinning methods were of significance to the site extraction volumes, extraction volumes per hectare, extraction carbon content per hectare, and extraction ratios. Land use classifications were of significance to the extraction volumes per hectare, extraction carbon content per hectare, extraction carbon content per tree, and extraction ratios; in particular, forest recreation areas exhibited significantly lower site extraction volumes and extraction ratios than did the other land use types. Tree species were also of significance to extraction ratios, revealing that the SP2 and SP4 groups had the highest extraction ratios. ANOVA results suggested that the age class was of significance to the extraction volumes per tree.

3.3. Duncan's New Multiple Range Test (MRT)

Table 8 shows that thinning methods were not subjected to the post hoc test because the logs felled through cleaning were not extracted; hence, their extraction volume was obviously lower than those of the other methods. Land use classifications were of significance to the site extraction volumes, extraction volumes per hectare, and extraction ratios. Duncan's MRT results indicated that both the timber management areas and national protected areas had higher site extraction volumes, extraction volumes per hectare, and extraction ratios compared with the forest recreation areas. Tree species were of significance to the extraction ratios. Results of the Duncan's MRT indicated that the group of SP2 had a significantly higher extraction ratio than the SP6 group. The group of SP5 had a significantly lower extraction ratio than the SP1, SP2, SP3, and SP4 groups.

Table 5. Relationships between site/species attributes and extraction volumes.

Item	Age Class				Thinning Method				Land Use Classification				Species			
		Num.	Mean	StdDev		Num.	Mean	StdDev		Num.	Mean	StdDev		Num.	Mean	StdDev
Site extraction volume	AC1	4	267.88	331.73	TT1	6	679.37	660.56	LC1	42	580.94	485.02	SP1	29	549.73	523.05
	AC2	20	525.47	506.63	TT2	36	492.15	432.98	LC2	11	758.61	698.55	SP2	8	424.23	268.62
	AC3	23	762.27	600.20	TT3	7	0.00	0.00	LC3	10	122.00	103.78	SP3	10	689.12	520.43
	AC4	5	445.31	226.93	TT4	3	1012.52	132.65					SP4	7	724.79	865.93
	AC5	8	291.93	385.72	TT5	1	990.59						SP5	4	113.81	130.25
	AC6	3	96.36	102.51	TT6	4	765.50	366.22					SP6	5	441.62	341.23
					TT7	6	846.77	883.52								
Extraction volume per hectare	AC1	4	10.79	18.25	TT1	6	64.47	44.59	LC1	42	51.02	50.72	SP1	29	52.57	58.43
	AC2	20	36.91	26.01	TT2	36	49.48	48.64	LC2	11	69.23	37.45	SP2	8	45.31	13.71
	AC3	23	55.09	44.32	TT3	7	0.00	0.00	LC3	10	15.64	13.67	SP3	10	69.21	42.88
	AC4	5	63.58	46.92	TT4	3	47.76	11.59					SP4	7	44.20	38.59
	AC5	8	80.35	84.12	TT5	1	123.82						SP5	4	15.55	10.88
	AC6	3	17.31	3.11	TT6	4	85.92	44.22					SP6	5	22.04	18.78
					TT7	6	47.04	41.88								
Extraction volume per tree	AC1	4	0.03	0.04	TT1	6	0.15	0.07	LC1	42	0.14	0.14	SP1	29	0.18	0.22
	AC2	20	0.11	0.08	TT2	36	0.19	0.22	LC2	11	0.25	0.25	SP2	8	0.18	0.08
	AC3	23	0.14	0.11	TT3	7	0.00	0.00	LC3	10	0.17	0.27	SP3	10	0.14	0.08
	AC4	5	0.24	0.18	TT4	3	0.15	0.08					SP4	7	0.13	0.12
	AC5	8	0.29	0.33	TT5	1	0.16						SP5	4	0.25	0.43
	AC6	3	0.37	0.46	TT6	4	0.30	0.19					SP6	5	0.08	0.07
					TT7	6	0.14	0.13								

Note: Age class: AC1 = 1–20 years, AC2 = 21–30 years, AC3 = 31–40 years, AC4 = 41–50 years, AC5 = 51–60 years, and AC6 = over 60 years; Thinning method: TT1 = three-row clear cutting, eight-row thinning, TT2 = low thinning, TT3 = cleaning, TT4 = intermediate/low thinning, TT5 = gap thinning, TT6 = rows, and TT7 = selective cutting; Land use: LC1 = timber management area, LC2 = national protected area, and LC3 = forest recreation area.

Table 6. Relationships between site/species attributes and extraction ratios.

Item	Age Class				Thinning Method				Land Use Classification				Species			
		Num.	**Mean**	**StdDev**		**Num.**	**Mean**	**StdDev**		**Num.**	**Mean**	**StdDev**		**Num.**	**Mean**	**StdDev**
Extraction ratio	AC1	4	28.29	35.68	TT1	6	51.78	25.77	LC1	41	56.76	29.71	SP1	27	56.83	33.28
	AC2	19	55.18	27.71	TT2	31	65.32	23.81	LC2	11	73.42	19.35	SP2	8	77.39	8.86
	AC3	22	62.79	29.53	TT3	7	0	0	LC3	6	29.68	40.59	SP3	9	56.97	22.37
	AC4	4	84.9	15.44	TT4	3	79.68	12.26					SP4	7	66.03	32.7
	AC5	7	50.62	36.88	TT5	1	74.32						SP5	3	7.76	7.27
	AC6	2	37.93	41.11	TT6	4	71.95	4.21					SP6	4	40.31	29.36
					TT7	6	62.7	34.85								
	Total	58	57.12	30.99		58	57.12	30.99		58	57.12	30.99		58	57.12	30.99

Note: Refer to Table 5 for a description of the codes.

Table 7. ANOVA for the site/species attributes and carbon content for extracted wood.

	Age Class		Thinning Method		Land Use Classification		Species	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Site extraction volume	2.03	0.09	2.77	0.02 *	4.81	0.01 **	0.98	0.44
Extraction volume per hectare	2.13	0.08	2.54	0.03 *	3.91	0.03 *	1.18	0.33
Extraction volume per tree	2.67	0.03 *	1.38	0.24	1.76	0.18	0.45	0.81
Site extraction carbon content	1.53	0.20	1.22	0.31	2.85	0.07	1.30	0.28
Extraction carbon content per hectare	2.26	0.06	2.34	0.04 *	6.07	0.00 **	1.22	0.31
Extraction carbon content per tree	2.36	0.05 *	1.66	0.15	5.81	0.00 **	0.95	0.46
Extraction ratio	1.84	0.12	8.89	0.00 **	4.33	0.02 *	3.01	0.02 *

Note: Interaction terms, which are often needed for regression analysis, are not included here. * $p < 0.05$. ** $p < 0.01$.

Table 8. Post hoc test with Duncan's MRT.

	Age Class	Land Use Classification	Species
Site extraction volume		LC1, LC2 > LC3	
Extraction volume per hectare		LC1, LC2 > LC3	
Extraction volume per tree	AC5 > AC1; AC6 > AC1, AC2, AC3		
Extraction ratio		LC1, LC2 > LC3	SP2 > SP6; SP5 < SP1, SP2, SP3, SP4

Note: Refer to Table 5 for a description of the codes.

4. Discussion

Thinning has been commonly used for adjusting the growth rate, size, and form of individual trees. Thinning is also associated with management of structure and volume of stands [18–20]. Considering that more than 95% of Taiwan's energy sources are imported, wood from thinning can serve as a fuel for bioenergy. Although some high-quality wood from thinning is suitable for furnishings, moving them out of the forest is usually difficult. Currently, wood from thinning can be either used as firewood or made into wood pellets as bioenergy. The wood pellets from thinned wood have similar qualities in the context of bioenergy use. Since transporting all thinned logs out of the forest is not possible, it is critical to investigate the extraction ratio in order to determine the net carbon benefit from using thinned wood for bioenergy.

Thinning benefits under various conditions were investigated. As for the tree species, the SP4 (*C. formosensis or C. formosana*) group yielded the highest extraction volume per hectare, probably because these species held the highest timber prices. As for the thinning methods, TT4 (intermediate/low thinning) yielded the highest site extraction volume and TT5 (gap thinning) yielded the highest extraction volume per hectare. Site extraction volumes of TT3 (cleaning cutting) were zero because the method was usually applied to less-valuable trees with small diameters. Generally, an advance in age class improves the timber volume and quality, rendering it more valuable. As for the influence of land use classification, the results showed that the extraction volumes of LC1 (timber management area) were actually similar to those of LC2 (national protected area), and the extraction volumes of both areas were much higher than those of LC3 (forest recreation area). This is because the forests in both LC1 and LC2 are well protected, resulting in larger extraction volumes. In contrast, LC3 is designated for recreational use, thus the low site extraction volumes could probably be attributed to the high level of human activity in the form of trampling and damage to the soil, which impeded tree growth. Overall, the extraction ratio was relatively low because the logs were left on-site owing to the inconvenience of transportation, diseases and pests, and small tree diameters.

However, the carbon content of the thinned stands decreased accordingly because parts of the stands were removed [21–28]. This study showed that the first thinning was conducted mainly on young forests, and the effects of thinning on old forests remained unclear. *C. japonica* or *C. lanceolata* and *C. formosensis* or *C. formosana* (SP5) had less thinning volume, relatively less than the other species.

Regarding the thinning methods, this study showed no significant difference because there is only small difference in thinning intensity. The ages of thinned forests differed significantly for volume. For the stands with ages >50 years, larger thinning volume was observed, but the effects of retained wood and stands growth need further analysis.

This study also showed that the total stem volume, a large component of the aboveground carbon [29], of the stands thinned early is greater than that of the stands thinned later. Similar results can be found in previous works [30]. The thinning volume also increases more quickly from early-thinned forests than from late-thinned ones [30–33]. The thinning residual removal rate had a larger effect than thinning intensity when considering the ecosystem productivity [34]. Specifically, the lower thinning intensity and higher thinning residual removal rate are beneficial to the ecosystem productivity [35]. This study showed that other stand attributes, including size, density, and species composition, play an important role in determining aboveground carbon content, which is consistent with previous studies [36,37]. It is worth mentioning that forest thinning also releases the forest space. This potentially reduces the risk and scale of wildfires, thereby fixing more carbon in the wood, in addition to economic savings.

5. Conclusions

The collected data over a decade is of great importance for Taiwan's bioenergy plan. The extraction ratio measured in this research reflects how much of thinned logs can be used for bioenergy. Thinning benefits under various conditions (age class, thinning method, land use, species) were investigated. An extraction ratio of 57.12% is estimated from 52 thinning sites in Taiwan. In some cases, the extraction ratio could be zero. For example, no logs were extracted from cleaning cuts in less-valuable young stands. By contrast, the extraction ratio can even be higher than 100% because previously thinned wood, leftovers from natural mortality, and windbreaks could also be extracted. Generally, thinned logs with larger timber volume and high quality account for high thinned volumes, but the extraction volumes are directly affected by economic factors, mainly from costly transportation due to the small-scale thinning. This results in a relatively low extraction ratio.

Currently, Taiwan is making a large-scale thinning plan and promoting bioenergy in some areas. The extraction ratio will be improved because of these economic incentives. The research outcomes of this study could provide valuable information for forest thinning in green-energy policy making. The collected data can also feed different data synthesis for global forest-thinning studies. For a more comprehensive understanding of the carbon benefits of thinning, further investigation on the growth of remaining trees, the decomposition process of unextracted logs, and the use and destination of extracted logs is necessary.

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