Is the Economic Benefit of Mixed Forest Better than Pure Forest Considering Harvesting Intensity and Carbon Payment?

Yow-Ru Lin (jokerc1120@gmail.com)
National Chung Hsing University
Wan-Yu Liu
National Chung Hsing University

Research Article

Keywords: Even-aged pure forest, uneven-aged mixed forest, carbon payment, harvesting intensity

Posted Date: May 26th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1658848/v1

Is the Economic Benefit of Mixed Forest Better than Pure Forest Considering Harvesting Intensity and Carbon Payment?

Yow-Ru Lin[1] and Wan-Yu Liu[2,*]

Yow-Ru Lin[1]
Department of Forestry, National Chung Hsing University, Taichung 402, Taiwan
Email: jokerc1120@gmail.com
Tel: +886-4-22850158

Wan-Yu Liu[2]
Department of Forestry, National Chung Hsing University, Taichung 402, Taiwan
Innovation and Development Center of Sustainable Agriculture, National Chung Hsing University, Taichung 402, Taiwan
Email: wyliu@nchu.edu.tw
Tel: +886-9-14043000

[*] Correspondence author. Email: wyliu@nchu.edu.tw

Funding Statement
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declaration on conflict of interest
We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. We declare no conflict of interest.

Total number of characters, tables and figures
8083 characters, 7 tables, and 4 figures.

Contribution of co-authors
Two co-authors had together contributed to the completion of this article. Yow-Ru Lin was the first author analyzing the data, and drafted the manuscript; Wan-Yu Liu contributed to the investigation, data analysis, the results, conclusion, and as the corresponding author on their behalf throughout the review, editing, and submission process.

Is the Economic Benefit of Mixed Forest Better than Pure Forest Considering Harvesting Intensity and Carbon Payment?

Abstract

Applying clear-cutting to an even-aged pure forest is a conventional forest operation for wood production. However, this kind of operation is not suitable for sustainable management with multiple objectives. In contrast, mixed-forest is a forestation strategy that accommodates diversity. The goal of this study was to assess an operation model that transforms from an even-aged pure forest into a mixed forest. Analysis in which an even-aged pure forest of *Cryptomeria japonica* was cut under a fixed harvesting intensity and replanted with the native broad-leaved tree species *Cinnamomum camphora* were conducted. In this study, the primary income for the forest owner was derived from wood sales and carbon payments. After deducting the costs of afforestation, management, and cutting, the land expectation value was estimated. The effects of critical variables, such as cutting time, harvesting intensity, and carbon price, were analyzed. This study explored strategies by which value could be increased in the transition from an even-aged pure forest to a mixed forest. Feasible methods included reducing the costs of afforestation, management, and cutting while increasing carbon prices to increase profits from wood and carbon income. Higher harvesting intensity could contribute to greater production of *Cryptomeria japonica* and increase the area available for planting *Cinnamomum camphora*, resulting in greater profits from wood and carbon income. The net present value from market value would be from –8,428 USD/ha to –2,446 USD/ha and that from carbon value will be from 5,151 USD/ha to 6,895 USD/ha. However, this measure would also substantially affect forest ecology. A sole focus on increasing the production value of forestland will neglect the original goal of transforming from an even-aged pure forest into a mixed forest.

***Keywords*:** Even-aged pure forest, uneven-aged mixed forest, carbon payment, harvesting intensity

1. Introduction

Afforestation brings direct benefits and indirect benefits, both involving tangible and intangible values. Tangible value is quantified in currency, such as the income from harvested timber. Intangible value associates with the ecological benefits, including carbon sequestration, water conservation, land conservation, and protecting wildlife habitats. Afforestation also exhibits intangible contributions to stabilization of the microclimate environment (National Taiwan University Biodiversity Research Center, 2006).

Even-aged stands are normal for wood production after clear-cutting, which is usually applied to natural forests or plantations during a rotation period. Re-establishing an even-aged stand is simple and produces similarly sized wood. This forest renewal method has been commonly used in Taiwan to manage forests. However, the cleared land lacks the protection of the forest and soil erosion easily occurs in the beginning of forest stand renewal. The wildlife habitats in an even-aged pure forest are also destroyed after clear-cutting, causing devastation among animals. The monoculture of an even-aged pure forest involves low species diversity, increasing the vulnerability to meteorological factors and insect damage. Therefore, the even-aged pure stand does not meet the requirements for sustainable forests. In forest management, numerous strategies may be adopted to reduce the negative effects owing to large-scale clear-cutting. These strategies include gradually removing the upper story of trees, reducing the area of the forest renewal, extending the rotation period, planting forests of more than two species (particularly coniferous and broad-leaved mixed forests), and adopting a thinning approach (Nyland, 2002; Gagnon et al., 2003; Page and Cameron, 2006; Pothier and Marcel, 2008; Lin et al., 2010).

The goal of afforestation has gradually shifted from forest production to multiple objectives, including forest maintenance, biodiversity enhancement, and carbon emission reduction. Various forest management strategies have been developed to achieve these objectives. Of these strategies, mixed forest management naturally results in biological diversity and a mixed forest is more resistant to insect damage. A mixed forest can also enhance the aesthetic value of a landscape (De Deyn et al., 2004; Jactel et al, 2005; Haas et al., 2011; Dawud et al., 2016; Coll et al., 2018; Lin et al., 2014).

Taiwanese forests were dominated by even-aged pure forests, such as *Cryptomeria japonica*, *Cunninghamia lanceolata*, *Acacia confusa*, *Fraxinus griffithii*, *Cinnamomum camphora*, and *Pinus taiwanensis* in the early years. Since 1940's, the afforestation policy has been changed to selecting tree species suitable for the local environment. For example, *Michelia compressa, Cinnamomum camphora,* and *Calocedrus formosana* were chosen for northern Taiwan based on their characteristics. To mitigate insect damages, which can be caused by single-species afforestation, different tree species should be selected. The five most common species of coniferous and the five most common species of broad-leaved trees in Taiwan are usually selected. However, as described, the specific species for afforestation should be selected according to the environmental conditions (National Taiwan University Biodiversity Research Center, 2006).

Previous studies have focused on transformation from even-aged pure forests into mixed forests in Taiwan (Lin et al., 2010, Chiu et al., 2014). For example, Lin et al. (2010) conducted a study and recommended that the *Chilanshan* area has been to plant coniferous and broad-leaved trees after the row thinning of the *Cryptomeria japonica* pure forest. This strategy increases the economic value and maintaining income between the long rotation periods of the high-priced cypress stand. Chiu et al. (2014) conducted an experiment of using four levels of thinning on a *Calocedrus formosana* plantation. The study proposed that if the underwood of the stand is well cultivated, and appropriate re-thinning is applied to the upper story of *Calocedrus formosana*, then the growth and survival of the trees under the forest may be enhanced. This strategy also enhances the carbon sequestration efficiency of *Calocedrus formosana*. However, none of the previous studies take harvesting intensity and carbon payment into consideration in economic analysis.

The aim of this study was to estimate the land expectation value of logging an even-aged pure forest replanting the forest with a native broad-leaved tree species under a fixed harvesting intensity. Carbon payments, in addition to wood sales, were considered as the income for the forest owner. The costs associated with afforestation, management and logging were included in the model. This study also analyzed the critical variables, such as logging time, harvesting intensity, and carbon price. Specifically, the effects of these variables on the land expectation value for transforming from the even-aged pure forest into mixed forest were determined. The results of this study may serve as a reference for decision–making of the forestry sectors.

2. Methods and Materials

2.1. Theoretical Model[*]

2.1.1. Land expectation value for an even-aged pure forest

In this study, the even-aged pure forest (aged T_0 years) is set as the plantation forest. After T_1 year, the forest age is $T_0 + T_1$ and is ready for clear cutting. The costs incurred during T_1 are from management and clear-cutting. Sources of income during T_1 are carbon payments from carbon sequestration and sales of the harvested wood product (HWP). After clear cutting, the same tree species is reforested to T_2 year. The resultant planted forest is an even-aged pure forest aged T_0 years. Costs incurred during (T_2 – T_1) years are from afforestation and management. Sources of income are carbon payments from carbon sequestration during (T_2 – T_1) years. For a specified area, the land expected value (*LEV*) of an even-aged pure forest is evaluated as follows:

[*] This study mainly focuses on a changed forest phase. In the model of converting pure forest into mixed forest, the *Cryptomeria japonica* are cut and *Cinnamomum camphora* are then replanted to achieve mixed forests in the second round. By contrast, in the pure forest situation, the setting for the second rotation period is "making it grow to a pure forest for 20 years." Thus, the second timber income is not included in the setting.

$$LEV = W(A, T_0 + T_1)e^{-rT_1} + \int_0^{T_1} G(A,t)\, e^{-rt} dt - \int_0^{T_1} F(A)\, e^{-rt} dt - L(A, T_0 + T_1)e^{-rT_1}$$
$$+ \int_{T_1}^{T_2} G(A,t)\, e^{-rt} dt - \int_{T_1}^{T_2} F(A)\, e^{-rt} dt$$

where A is the total area of the planted forest (ha); $W(A,T) = p \times A \times f(T)$ is the income from HWP at time point T, in which p is the per-unit wood price (NTD/m^3) and $f(T)$ is the per-unit volume of wood at T (m^3/ha); $G(A,T) = g \times A \times c(T)$ is the total income from carbon payment, in which g is the per-unit carbon payment (NTD/ton CO_2) and $c(T)$ is the amount of CO_2 sequestration per unit volume of wood at T (ton CO_2/ha); $F(A)$ is the total cost of afforestation and management for the forestland of total area A (NTD); $L(A,T) = l \times A \times f(T)$ is the logging cost for the total land area at T, in which l is the per-unit logging cost (m^3/NTD); r is the discount rate that reflects the future values of income and costs to the present time.

2.1.2. LEV of transforming from the even-aged pure forest to the mixed forest

In this study, the planted forest (aged T_0 years) is the coniferous even-aged pure forest in the process of growing to the forest age of T_0 + T_1, at which point it may be cut, after native broad-leaved species is replanted. During T_1, costs include management and cutting expenses, and sources of income are carbon payments and HWP sales from the coniferous forest.

After cutting, the forest is replanted and transformed into an uneven-aged coniferous and broad-leaved mixed forest, and the forestry operation is continued for $T_2 - T_1$ years. The forest age of the planted native broad-leaved trees is T_0. In T_2, cutting and replanting are repeated. The costs during $T_2 - T_1$ included afforestation and management of the replanted native broad-leaved forest, as well as the management of the remaining coniferous forest in T_1 and the cutting, afforestation, and replanting of the original broad-leaved forest in T_2. Income is from carbon payments from mixed-forest carbon sequestration during $T_2 - T_1$ and from the sales of *HWP* from the cutting of the remaining coniferous population in T_2. If the area of the forest land is fixed, then the *LEV* from transforming from the even-aged pure forest into a mixed forest is as follows:

$$
\begin{aligned}
LEV = {} & W(aA, T_0 + T_1)e^{-rT_1} + \int_0^{T_1} G_1(A,t)\, e^{-rt} dt - \int_0^{T_1} F_1(A)\, e^{-rt} dt - L(aA, T_0 + T_1)e^{-rT_1} \\
& + W\big((1-a)aA, T_0 + T_1 + T_2\big)e^{-rT_2} + \int_{T_1}^{T_2} G_1\big((1-a)A, t\big)\, e^{-rt} dt + \int_{T_1}^{T_2} G_2(aA, t)\, e^{-rt} dt \\
& - \int_{T_1}^{T_2} F_1\big((1-a)A\big)\, e^{-rt} dt - \int_{T_1}^{T_2} F_2(aA)\, e^{-rt} dt - L\big((1-a)aA, T_0 + T_1 + T_2\big)e^{-rT_2} \\
& - F_2\big((1-a)aA\big)e^{-rT_2}
\end{aligned}
$$

where a is the cutting intensity (%); $c_1(T)$ and $c_2(T)$ are the amounts of CO_2 sequestration per-unit volume of wood (ton CO_2/ha) for the coniferous forest and the native broad-leaved forest at T, respectively; G_1 and G_2 are the total carbon payment amounts for the coniferous forest and the primitive broad-leaved forest, respectively; F_1 and F_2 are the afforestation and management costs for the coniferous forest and the primitive broad-leaved forest, respectively.

2.2. Materials and Variables

2.2.1. Tree species selection

Cryptomeria japonica is an important economic tree species in Taiwan. Its planted forest was distributed over land 1,000–2,000 m above sea level. The Fourth Forest Resources Survey Report (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022) indicated that the *Cryptomeria japonica* was distributed across a total area of approximately 41,390 ha, and the forest stock of unit area of planted *Cryptomeria japonica* was 388.89 m^3, which was the highest among planted coniferous forests. According to the Forestry Statistics (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022), the production of *Cryptomeria japonica* timber is 9,252.39 m^3, which is the highest production among conifer species in Taiwan.

Cinnamomum camphora is a native commercial tree species in Taiwan. It is widely distributed across areas below altitudes of 1,200 m in northern Taiwan and those below 1,800 m in southern Taiwan. The optimal growth altitude of the species is below 1,500 m (Feng and Li, 2009). Lin et al. (2016) reported that the Forestry Bureau personnel responsible for afforestation recommended both *Cryptomeria japonica* and *Cinnamomum camphora* for afforestation. Specifically, *Cinnamomum camphora* was recommended because it exhibits a high survival rate, can be planted in various environments, and has a variety of use. Guo (2013) showed that *Cinnamomum camphora* can tolerate conditions of limited light in forests.

In this study of the transformation of an even-aged pure forest to a mixed forest, the replanting of trees at the lowest layers of the forest was assumed to enable the survival of trees in the canopy gaps of the cut coniferous forest. The species populating the planted coniferous forest in this study was *Cryptomeria japonica*, and the species of the native broad-leaved forest was *Cinnamomum camphora*.

2.2.2. Setting of forest age

The plantation forest in this study was set to be a mature forest, and the forest age was set as $T_0 = 20$. *Cryptomeria japonica* was selected as the conifer species, and *Cinnamomum camphora* was the native broad-leaved tree species. Both species are common afforestation species in Taiwan. According to the recommendations for afforestation tree species and corresponding rotation periods from the *Handbook of the Nationwide Reforestation Program* (Forestry Bureau, Council of Agriculture, Executive Yuan, 1998), the rotation period of *Cinnamomum camphora* is 30 years, and that of *Cryptomeria japonica* is 20 years. Considering a few studies have proposed a 30-year rotation period for *Cryptomeria japonica* (National Taiwan University Biodiversity Research Center, 2006), T_1 was set to be 10 years. In the *LEV* model of the even-aged pure forest, the planted forest land was set to grow into an even-aged pure forest of 20 years. In the *LEV* model for transforming from the even-aged pure forest to a mixed forest, T_2 was set to 30 years for the formation of the uneven-aged broad-leaved mixed forest.

2.2.3. Volume function (m^3/ha)

Based on the *Cryptomeria japonica* growth pattern proposed by Chang et al. (1987), the volume of *Cryptomeria japonica* can be estimated by the following formula:

$$V(T) = \exp(5.9027 - 25.6891 / T) \quad \text{(unit: m}^3\text{/ha)}$$

According to the growth pattern of *Cinnamomum camphora* proposed by Lin et al. (2002), the estimated volume of *Cryptomeria camphora* is given by the following formula:

$$V(T) = -18.934 + 11.69\,T - 0.0719\,T^2 \quad \text{(unit: m}^3\text{/ha)}$$

The total volume growth curve of *Cryptomeria japonica* and *Cinnamomum camphora* can be obtained by calculating the total volume at each forest age based on their growth patterns, as shown in Figure 1.

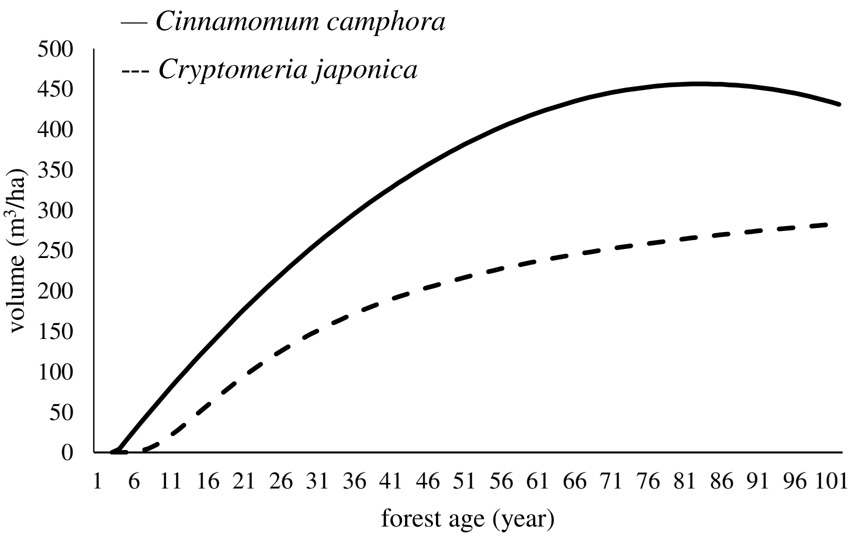

Figure 1. Growth curve of the total volumes of *Cryptomeria japonica* and *Cinnamomum camphora*.

2.2.4. Prices of HWP

Based on current wood use in Taiwan, the harvested wood was sorted into categories of wood products to determine the HWP sale value. According to the Food and Agriculture Organization of the United Nations (FAO), HWP categories include roundwood, sawnwood, wood-based panels, pulpwood, and wood chips (FAO, 2020). Chen et al. (2012) analyzed the use of wood materials in Taiwan and used solid wood equivalent volume to re-estimate the demand for wood materials. The results indicated that the proportion of demand for various wood materials in 2011 was: logs = 13%, sawnwood = 23%, wood-based panels = 27%, and pulpwood and wood chips = 37%. These proportions were used for the breakdown of HWP in this study.

To determine the price of HWP, this study calculated the average prices of roundwood, panels, and slabs of *Cryptomeria japonica* for the past 10 years (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022), which were 4,341, 10,623, and 5,756 NTD/m^3, respectively. The price of pulpwood and wood chips was set as 1,619 NTD/m^3 based on the average price of debarked branches over the past 10 years (Forestry Bureau, Council of Agriculture, Executive Yuan, 2017). According to the Wood Price Information System of the Forestry Bureau, the average price of *Cinnamomum camphora* roundwood over the past decade was 4,023 NTD/m^3.

2.2.5. Costs of afforestation and management

Under the operation scenario in the present study, afforestation was conducted after clear cutting of the even-aged pure forest. For transforming from an even-aged pure forest to a mixed forest, a procedure of replanting native broad-leaved trees after cutting a coniferous forest was implemented. The costs of afforestation and management should be considered. In the study by Liu et al. (2009), the cost of afforestation was broken down according to costs from raising seedlings, outplanting, and weeding. Under the current regulation, the costs of raising seedlings can be estimated. For example, the forest owner must pay 30,000 NTD/ha for the first year of outplanting if certain conditions are met. Regarding outplanting and weeding, there are guidelines about the required manpower and wage according to the Forestry Bureau, Council of Agriculture, Executive Yuan (2002, 2022). For example, 1-year-old planted forest land should be weeded twice a year, each round of weeding requires 8 labor–days/ha, and weeding workers needs to be paid 1,500 NTD each day.

2.2.6. Cutting-related costs

This study examined the operation scenario of clear cutting an even-aged pure planted forest. An even-aged pure planted forest must be clear cut to facilitate transformation to a mixed forest. Zheng and Shih (2006) applied regression analysis to the cost of forest cutting and the operation data of 46 leased national forestlands under the management of the Nantou Forest

District Office. The average cutting cost per cubic meter of leased national forestland was determined to be 1,493 NTD/m^3.

2.2.7. Carbon payment

Increased greenhouse gas emissions are the primary cause of climate change. Forests can absorb and store carbon dioxide, and this forest-based process is a crucial means for reducing greenhouse gas emissions. This study incorporated carbon payments in the operation scenarios for even-aged pure forests and for transforming from an even-aged pure forest to a mixed forest. The effect of transforming from the forest tree species composition on carbon sequestration benefits was analyzed. The carbon dioxide storage transformation formula proposed by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (IPCC, 1996) is given by

$$B = V \times V_T \times W_T$$

$$C_{CO_2} = B \times C_T \times (\mathrm{CO_2/C})$$

where B is the biomass per hectare (ton/ha), V is the wood volume per hectare (m^3/ha), V_T is the transformation coefficient between the whole tree volume and the dry wood volume, W_T is the transformation coefficient regarding weight and volume; C_{CO_2} is the CO_2 storage amount per hectare (ton CO_2/ha), C_T is the transformation coefficient for carbon content, and CO_2/C is the transformation coefficient for carbon dioxide and carbon.

Table 1 presents the key parameters for carbon dioxide storage of *Cryptomeria japonica* and *Cinnamomum camphora.* The wood volume was transformed into whole-tree volume, and the specific weight of wood was multiplied to obtain the forest biomass. Subsequently, the forest biomass was multiplied by the transformation coefficients of carbon and carbon dioxide 3.67, to determine the amount of carbon dioxide that could be stored. Figure 2 presents the carbon dioxide storage curves of *Cryptomeria japonica* and *Cinnamomum camphora*.

Based on the Greenhouse Gas Reduction and Management Act of the Environmental Protection Administration, Executive Yuan (2022), this study assumed the carbon payment of CO_2 per ton to be 1,500 NTD.

Table 1. Key parameters for the carbon dioxide storage (Lin et al., 2002).

Species	V_T	W_T	C_T
Cryptomeria japonica	1.6633	0.302	0.4974
Cinnamomum camphora	1.67	0.395	0.47

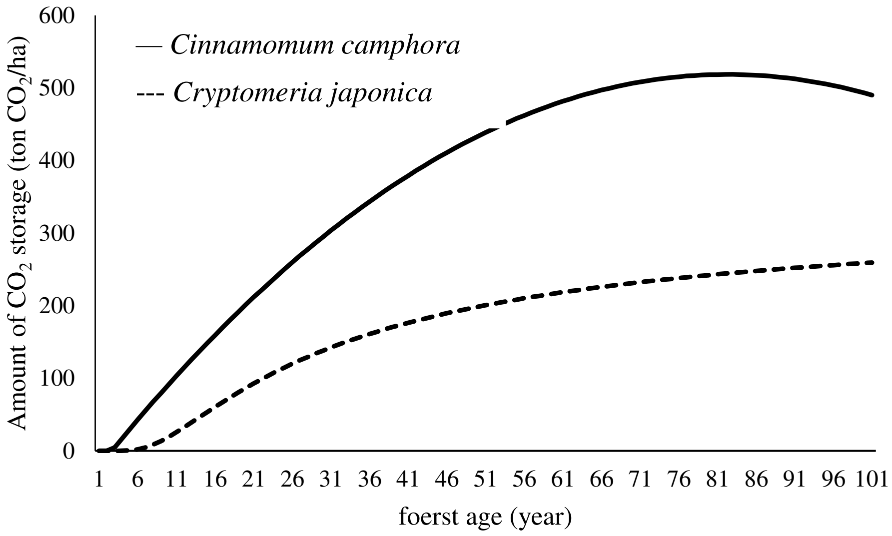

Figure 2. Carbon dioxide storage curves of *Cryptomeria japonica* and *Cinnamomum camphora*.

2.2.8. Discount rate

This study used the LEV model to analyze operation scenarios for an even-aged pure forest and for transforming from the even-aged pure forest to a mixed forest. To analyze and compare each scenario at the same time point, the future income and costs for the 20-year-old planted forest land were considered. The current preferential interest rate of afforestation loan (1.25%) was used as the discount rate in this study (Bureau of Agricultural Finance, Council of Agriculture, Executive Yuan, 2016).

2.2.9. Scenario setting[†]

[†]In the case of converting a same-age pure forest into a mixed forest, this study gradually removes *Cryptomeria japonica*, narrows the area of forest renewal, extends the rotation period, and builds a mixed forest of two species to reduce the negative impact caused by large-scale clear cutting.

A. Scenario for an even-aged pure forest (Figure 3).

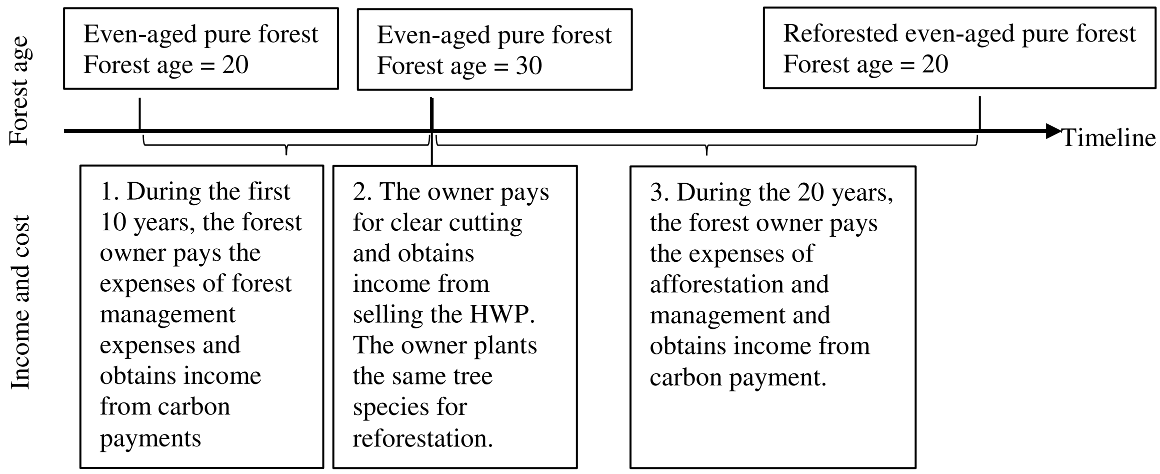

Figure 3. Scenario for an even-aged pure forest.

B. Scenario of transforming from an even-aged pure forest to a mixed forest (Figure 4).

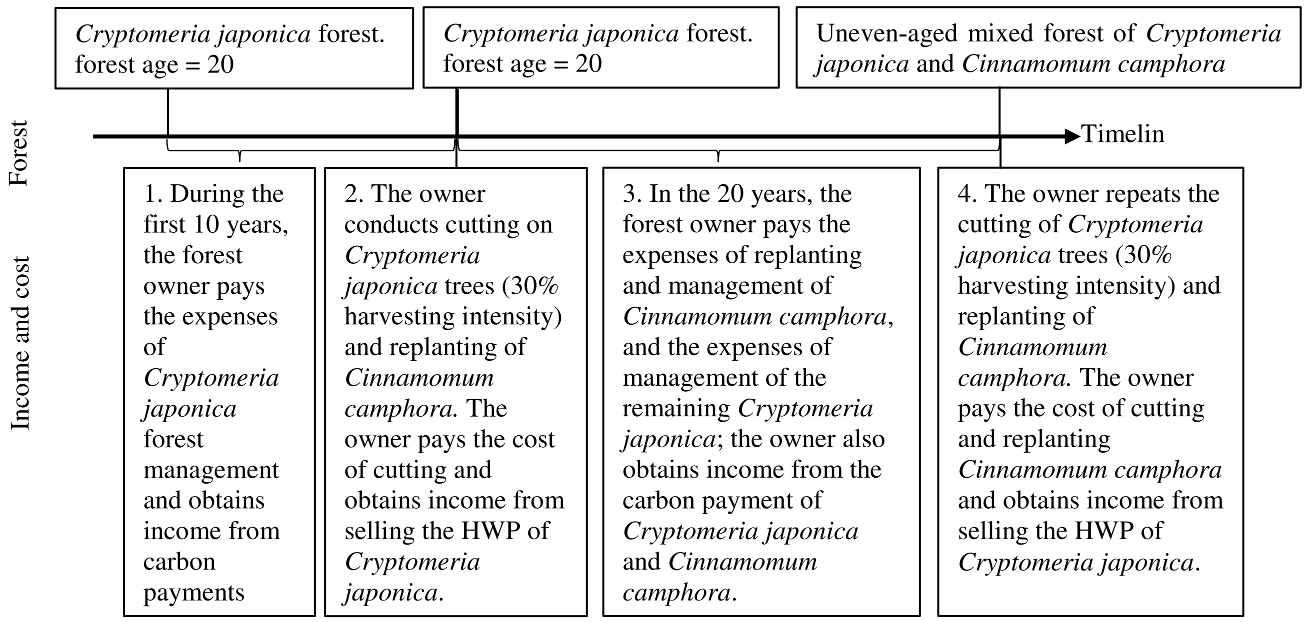

Figure 4. Scenario of transforming from an even-aged pure forest into a mixed forest.

3. Results

3.1. LEV of even-aged pure forest

This study calculated the model of per-unit LEV for the 20-year-old even-aged pure forest of *Cryptomeria japonica* and for that of *Cinnamomum camphora*. The initial forest age was set to 20. Clear cutting and reforestation using the same tree species were implemented when the forest reached the age of 30, and the forest grew into an even-aged pure forest of forest age 20. The forest owner obtained wood income when the forest was 30 years old. The forest owner obtained a total of 30 years' worth of carbon payments, specifically for the years of forest age 20–30 and for the 20 years of reforestation. The individual net present value of income from unit wood, and net present value of per-unit carbon payment, and per-unit LEVs of the two pure forests are presented are presented in Table 2. As can be seen, the unit LEV from planting *Cinnamomum camphora* in the even-aged pure forest was 293,249 NTD higher than that from planting *Cryptomeria japonica.* Specifically, the net present value of the unit wood income from *Cinnamomum camphora* was 93,064 NTD higher than that from *Cryptomeria japonica*, and the net present value of the per-unit carbon payment for *Cinnamomum camphora* was 200,185 NTD higher than that for *Cryptomeria japonica*.

Despite the average unit price for *Cryptomeria japonica* HWP (5,161 NTD) being higher than that for *Cinnamomum camphora* (4,023 NTD), the growth curves of *Cryptomeria japonica* and *Cinnamomum camphora* (see Figure 1) illustrate that the unit stock of

Cinnamomum camphora was higher than that of *Cryptomeria japonica.* Although planting *Cinnamomum camphora* for the even-aged pure forest involved higher cutting-related costs, income from *Cinnamomum camphora* wood was higher than that from *Cryptomeria japonica* wood. According to the curves of carbon dioxide storage for *Cryptomeria japonica* and *Cinnamomum camphora* (see Figure 2), the unit stock of *Cinnamomum camphora* was higher than that of *Cryptomeria japonica.* Carbon dioxide storage was calculated based on the growth of *Cinnamomum camphora*, and the results indicated that the amount of carbon dioxide storage was higher than that of *Cryptomeria japonica.* Additionally, during the 30 years of forest growth, the slope of the carbon dioxide storage curve of *Cinnamomum camphora* was steeper than that of *Cryptomeria japonica*. Thus, the carbon payment was higher in the model of planting *Cinnamomum camphora* in the even-aged pure forest. Accordingly, the per-unit LEV of the operation model of planting *Cinnamomum camphora* in the even-aged pure forest was higher than that of planting *Cryptomeria japonica*.

Table 2. LEV of even-aged pure forest.

Tree species	Net present value of income per unit of wood (NTD/ha)	Net present value of unit carbon payment (NTD/ha)	Per-unit LEV (NTD/ha)
Even-aged pure forest of *Cryptomeria japonica*	4,633	173,877	178,510
Even-aged pure forest of *Cinnamomum camphora*	97,697	374,062	471,759

3.2. LEV of Transformation from an even-aged pure forest into a mixed forest

This study set the initial forest age as 20. Cutting with under 30% harvesting intensity and replanting of *Cinnamomum camphora* were conducted at the 30th year to transform from the *Cryptomeria japonica* forest into a mixed forest. The mixed forest continued to grow for another 20 years, after which the cutting and replanting procedures were repeated. The forest owner obtained wood income from cutting the *Cryptomeria japonica* forest when the *Cryptomeria japonica* was 30 years old and when the mixed forest was 20 years old. The forest owner obtained carbon payments for the years when the *Cryptomeria japonica* forest was aged 20–30 and for the 20 years of mixed forest growth, for a total of 30 years' worth of carbon payments. Table 3 shows the results for per-unit LEV in the basic scenario of transforming from an even-aged pure forest into a mixed forest. The net present value of per-unit wood income in the basic scenario was calculated to be −124,259 NTD; the net present value of per-unit carbon payment was 191,317 NTD; and the per-unit LEV was 67,057 NTD.

Table 3. LEV for transforming from an even-aged pure forest into a mixed forest.

Basic scenario of transforming from an even-aged pure forest into a mixed forest	Net present value of income per unit of wood (NTD/ha)	Net present value of per-unit carbon payment (NTD/ha)	Per-unit LEV (NTD/ha)
Cutting and replanting *Cinnamomum camphora* in the 10th and 30th years	-124,259	191,317	67,057

3.3. Different cutting time

This study analyzed and compared results for various time points of cutting *Cryptomeria japonica* and then replanting *Cinnamomum camphora*. Specifically, results for cutting at the 10th, 15th, and 20th years under a 30% harvesting intensity were calculated For all scenarios cutting and replanting were repeated in the 30th year. The forest owner obtained wood income from the two cuttings of *Cryptomeria japonica*. In addition, the forest owner obtained annual carbon payments from cutting at the initial time point up to various cutting times and during the growth time of the mixed forest, for a total of 30 years' worth of carbon payments.

The results for this scenario are presented in Table 4 and Figure 6. The net present value of per-unit wood income, the net present value of per-unit carbon payments, and the per-unit LEV were lower at later cutting times. Later cutting times corresponded with increased costs of afforestation and management of *Cryptomeria japonica* during the cutting period. Moreover, the growth of *Cryptomeria japonica* increased the costs of cutting; thus, the net present value of per-unit wood income decreased from −124,259 to −125,645 when cutting time was delayed. The results for the even-aged pure forest indicated that *Cinnamomum camphora* stored a greater amount of carbon dioxide than did *Cryptomeria japonica*; thus, the carbon payment for *Cinnamomum camphora* was higher. However, delayed cutting time reduced growth time of the replanted *Cinnamomum camphora*, and the carbon payment amount was slightly lower.

Specifically, the net present value of per-unit carbon payment decreased from 191,317 NTD to 163,985 NTD. Therefore, the per-unit LEV decreased from 67,057 NTD to 38,341 NTD when cutting time was delayed.

Table 4. LEV for various cutting time points.

Cutting time points	Net present value of income per unit of wood (NTD/ha)	Net present value of per-unit carbon payment (NTD/ha)	Per-unit LEV (NTD/ha)
Replanting *Cinnamomum camphora* in the 10th year	-124,259	191,317	67,057
Replanting *Cinnamomum camphora* in the 15th year	-122,918	178,421	55,503
Replanting *Cinnamomum camphora* in the 20th year	-125,645	163,985	38,341

3.4. Different Harvesting Intensity

This study analyzed and compared LEVs with various harvesting intensities. The initial *Cryptomeria japonica* forest age was set to be 20. The scenario was the transformation of a same-age pure forest into a mixed forest. Three harvesting intensities were analyzed and compared. Specifically, results were examined for replanting with *Cinnamomum camphora* after cutting with harvesting intensities of 10%, 20%, and 40%, where the cutting and replanting were repeated in the 30th year for all cases. With total amount based on the harvesting intensity, the forest owner obtained wood income when the *Cryptomeria japonica* forest was 30 years old and when the mixed forest was 20 years old. Additionally, the owner obtained annual carbon payments for the *Cryptomeria japonica* forest at forest age 20–30 and for the 20 years of mixed forest growth, for a total of 30 years' worth of carbon payments.

Table 5 shows the results for cutting *Cryptomeria japonica* and replanting with *Cinnamomum camphora* according to the aforementioned conditions. The net present value of per-unit wood income, the net present value of per-unit carbon payment, and the per-unit LEVs all rose with increases of harvesting intensity. Increases in cutting intensity resulted in increased costs of cutting *Cryptomeria japonica* and costs of replanting with *Cinnamomum camphora*, but increased cutting intensity also corresponded with greater income from greater sales of *Cinnamomum camphora* HWP. Specifically, the net present value of per-unit wood income increased from −255,403 NTD to −74,134 NTD. The results for the even-aged pure forest revealed that the carbon dioxide storage of *Cinnamomum camphora* was greater than that of *Cryptomeria japonica*; thus, the carbon contribution value of *Cinnamomum camphora* was higher. In addition, the area of replanted *Cinnamomum camphora* increased with rising harvesting intensity, contributing an increase in the net present value of per-unit carbon payment from 156,076 NTD to 208,937 NTD. Therefore, the per-unit LEV increased from −99,327 NTD to 134,804 NTD with the increase of harvesting intensity.

Table 5. LEV for various harvesting intensities.

Harvesting intensity	Net present value of the income per unit wood (NTD/ha)	Net present value of per-unit carbon payment (NTD/ha)	Per-unit LEV (NTD/ha)
10%	-255,403	156,076	-99,327
20%	-184,682	173,696	-10,986
30%	-124,259	191,317	67,057
40%	-74,134	208,937	134,804

3.5. Different carbon payments

This study analyzed and compared LETs under various carbon prices. The carbon payments were calculated based on the Greenhouse Gas Reduction and Management Act of the Environmental Protection Administration, Executive Yuan (2022). Specifically, the carbon payment was set to be 1,500 NTD per ton of carbon dioxide. The initial *Cryptomeria japonica* forest age was set to be 20. When the forest reached the age of 30, it was cut at 30% harvesting intensity, and replanting was conducted using *Cinnamomum camphora*. Thus, the pure forest was transformed to a mixed forest. The operation was continued for 20 years, after which the cutting and replanting procedures were repeated. The forest owner obtained wood income from *Cryptomeria japonica* when it was 30 years old and the mixed forest was 20 years old. Under various carbon prices, the income of the forest owner was the sum of the carbon payments for *Cryptomeria japonica* at the forest age of 20–30 and the carbon payments received during the 20 years of mixed forest growth. Thus, in total, 30 years' worth of annual carbon payments from the production of *Cryptomeria japonica* and *Cinnamomum camphora* were received.

Table 6 presented the results. The net present value of per-unit carbon payment and the per-unit LEV rose with increases in carbon payment. The wood income was not affected by carbon payment. Thus, the net present value of per-unit wood income was fixed at −124,259 NTD. Specifically, the net present value of per-unit carbon payment increased from 64,680 NTD to 637,723 NTD. Accordingly, the per-unit LEV gradually increased from −59,579 NTD to 513,464 NTD.

Table 6. LEV of different carbon payments.

Carbon payments (ton CO_2/NTD)	Net present value of the income from each unit of wood (NTD/ha)	Net present value of unit carbon payment (NTD/ha)	Per-unit LEV (NTD/ha)
507.12*	-124,259	64,680	-59,579
1,000	-124,259	127,545	3,285
1,500**	-124,259	191,317	67,057
2,000	-124,259	255,089	130,830
3,000	-124,259	382,634	258,374
4,000	-124,259	510,178	385,919
5,000	-124,259	637,723	513,464

* Based on the carbon price announced by the European Union Emission Trading Scheme (EU ETS) (EU ETS Carbon Pulse, 2022), the carbon price was set to be 507.12 (NTD/ton CO_2) (according to the foreign exchange rate on April 2, 2022 announced by the Bank of Taiwan).
** Based on the Greenhouse Reduction and Management Act of the EPA (2022), the carbon price was set to be 1,500 (NTD/ton CO_2).

4. Discussions

This study explored an operation model of transforming from an even-aged pure forest into a mixed forest. Analysis and comparison of operation models of the even-aged pure forest indicated that the LEV of planting *Cinnamomum camphora* was higher than that of planting *Cryptomeria japonica*. Therefore, although the cost of cutting *Cinnamomum camphora* was higher, the wood income from *Cinnamomum camphora* was still higher than that from *Cryptomeria japonica*. The amount of CO_2 storage noted for the growth model of *Cinnamomum camphora* also was higher than that of *Cryptomeria japonica*, indicating that the carbon payment from planting *Cinnamomum camphora* was higher than that of *Cryptomeria japonica*.

An even-aged pure forest was transformed to that of a mixed forest in the 10th year, and replanting with *Cinnamomum camphora* was conducted after *Cryptomeria japonica* was cut at 30% harvesting intensity. Growth into an unevenly aged coniferous, broad-leaved mixed forest formed continued until the 30th year, at which point the same cutting procedure was repeated, yielding a per-unit LEV was 67,057 NTD. Later cutting time caused an increase in costs of afforestation, management, and cutting of *Cryptomeria japonica*. After replanting with *Cinnamomum camphora*, carbon payments were lower; thus, the per-unit LEV decreased. Increase in harvesting intensity resulted in higher income from selling the HWP of *Cryptomeria japonica* as well as an increased area replanted with *Cinnamomum camphora*. Carbon payment increased after cutting *Cryptomeria japonica* and replanting with *Cinnamomum camphora*, in turn resulting in an increase in per-unit LEV.

Because the unit stock of *Cinnamomum camphora* was high, the net present value of the per-unit wood income was high. Therefore, the operation model of the even-aged pure forest of *Cinnamomum camphora* maximized the net present value of wood income, which was 97,697 NTD/ha. For the model of transforming from an even-aged pure forest into a mixed forest, the wood income was not derived from cutting *Cryptomeria japonica* at 30% harvesting intensity. A total of 51% of the *Cryptomeria japonica* forest was cut and was replanted with *Cinnamomum camphora*. After deducting related expenses such as afforestation and cutting, the net present value of per-unit wood income was only −124,259 NTD/ha.

The even-aged pure forest of *Cinnamomum camphora* exhibited the highest net present value of per-unit carbon payment, because the unit stock of *Cinnamomum camphora* was high and thus correlated with a relatively high amount of CO_2 storage. Specifically, the result for per-unit carbon payment was 374,062 NTD/ha. For transforming an even-aged pure forest into a mixed forest, the *Cryptomeria japonica* was cut and replanted with *Cinnamomum camphora*, which exhibited greater carbon sequestration efficiency. These measures increased the income from carbon payments for the original forestland. The net present value of the per-unit carbon payment was as 191,317 NTD/ha, which was 17,440 NTD/ha higher than that of the even-aged pure forest of *Cryptomeria japonica*. Especially, the even-aged pure forest of *Cinnamomum camphora* exhibited the highest LEV, at 471,759 NTD/ha. The net present values of per-unit wood income and per-unit carbon payments for the even-aged pure forest of *Cinnamomum camphora* were much higher than those for the mixed forest transformed from an even-aged pure forest.

As for the harvesting intensity, greater harvesting intensity resulted in higher production for the *Cryptomeria japonica* forest as well as a larger area for planting *Cinnamomum camphora*, in turn increasing income from wood and carbon payments. It is noted that greater harvesting intensity would substantially affect forest ecology. Forestry strategies that only focus on increasing the output value of the forestland neglect the initial purpose of transforming from an even-aged pure forest into mixed forest.

5. Conclusions

In this study, *Cryptomeria japonica* products were classified as logs, sawnwood, wood-based panels, and pulpwood and wood chips, and prices were assigned based on the classifications of HPW defined by the FAO, the results of Chen et al. (2012), the Wood Price Information System (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022), and the prices in the forestry statistics (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022). However, for *Cinnamomum camphora*, only the log price was published in the wood market price information system, and the forestry statistics (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022) did not provide species-specific production details. Therefore, price setting for *Cinnamomum camphora* products could be improved in subsequent studies. The government should update the information system regarding market prices for wood products.

Such updated information may benefit decision–making in the forestry sector and serve as a reference for academic research and enquiry.

To incentivize forest owners to invest in the mixed forest, the government should establish a reliable carbon trading system and raise the standards and penalties of the Greenhouse Gas Reduction and Management Act. In addition to researching and developing green technology and strategies for pollution prevention, the government may consider adopting forestry operations as the primary method for reduction of carbon emissions. Forest owners can provide carbon storage, which can be sold to meet enterprises and factories' demands for carbon emissions reductions. These transactions could form a carbon trading market that would increase the incomes of forest owners and enable them to invest in mixed forests. This may even encourage enterprises to invest in planting forests, thereby increasing forest coverage and the associated effects of carbon-sinks in Taiwan.

In actual situations, values may fluctuate with the prices of raw materials and wages, and the growth of a forest would also affect the cost of afforestation, management, and cutting. Additionally, only a 30-year operation period for transforming from an even-aged pure forest into a mixed forest was considered. In follow-up research, analysis based on other periods can be conducted to enhance the comprehensiveness of the operation model for a mixed forest. Last but not the least, this study did not consider the proportion of carbon emissions in the scenarios, nor the uses of the HWPs. Cutting and wood use types affect the carbon emissions of a forest.

Future studies should consider carbon emissions to determine the actual value of carbon payments.

References

Chang, Joseph S., Chen, L.-C., & Jen, I-A. (1987) An analysis of the growth and yield of man-made forest in Taiwan. *Bulletin of Taiwan Forestry Research Institute*, 2(1), 17-29.

Chen, L.-C., Lin, J.-C., Wu, C.-S., Huang, G.-M., & Chen, Y.-H. (2012) The current status of the wood product demand in Taiwan. *Quarterly Journal of Forest Research*, 34(4), 287-296.

Chiu, C.-M., Su, S.-H., Tang, S.-L., & Fuh, C.-H. (2014) Assessing the benefits of thinning and underplanting of broadleaved trees in a Taiwan incense-cedar plantation. *Quarterly Journal of Chinese Forestry*, 47(2), 137-154.

Coll, L., Ameztegui, A., Collet, C., Löf, M., Mason, B., Pach, M., Verheyen, K., Abrudan, I., Barbati, A., Barreiro, S., Bielak, K., Bravo-Oviedo, A., Ferrari, B., Govedar, Z., Kulhavy, J., Lazdina, D., Metslaid, M., Mohren, F., Pereira, M., Peric, S., Rasztovits, E., Short, I., Spathelf, P., Sterba, H., Stojanovic, D., Valsta, L., Zlatanov, T., & Ponette, Q. (2018) Knowledge gaps about mixed forests: What do european forest managers want to know and what answers can science provide? *Forest Ecology and Management*, 407, 106-115.

Dawud, S.M., Raulund-Rasmussen, K., Domisch, T., Finér, L., Jaroszewicz, B., & Vesterdal, L. (2016) Is tree species diversity or species identity the more important driver of soil carbon stocks, C/N Ratio, and pH? *Ecosystems*, 19, 645-660.

De Deyn, G.B., Raaijmakers, C.E., van Ruijven, J., Berendse, F., & van der Putten, W.H. (2004) Plant species identity and diversity effects on different trophic levels of nematodes in the soil food web. *Oikos*, 106, 576-586.

Environmental Protection Administration, Executive Yuan (2022) Greenhouse Gas Reduction and Management Act. https://goo.gl/Gaijp3/ (accessed April 1, 2022).

EU ETS Carbon Pulse (2022) EU ETS Carbon Pulse. https://goo.gl/SJGuQ4/ (accessed April 1, 2022).

FAO (2020) *Yearbook of Forest Products 2018*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). 358pp.

Feng, F.-L., & Lee, H.-T. (2009) The status and perspectives of camphor tree in Taiwan. *Biological Science*, 51(2), 37-51.

Forestry Bureau, Council of Agriculture, Executive Yuan (1998) *Handbook of the Nationwide Reforestation Program*. Taipei, Taiwan: Forestry Bureau, Council of Agriculture, Executive Yuan.

Forestry Bureau, Council of Agriculture, Executive Yuan (2002) Forest Rule No.0910000477, Online Inquiry System-Forestry Bureau, Council of Agriculture, Executive Yuan. https://goo.gl/kX5Jg8/ (accessed April 1, 2022).

Forestry Bureau, Council of Agriculture, Executive Yuan (2011) Plan chart for Afforestation Areas, Coastal Forest Afforestation, National Collapsed Land Revegetation, and Afforestation and Seedling-raising for Coastal Forests at Outlying Islands. Ilan, Taiwan: Luodong Forest District Office of the Forestry Bureau.

Forestry Bureau, Council of Agriculture, Executive Yuan (2022) The 4th Forest Resources Survey Report. https://goo.gl/75Xpd5/ (accessed April 1, 2022).

Bureau of Agricultural Finance, Council of Agriculture, Executive Yuan (2022) Regulations on Afforestation Loan, Agricultural Project Loans. https://goo.gl/HkZW6u/ (accessed

April 1, 2022).

Forestry Bureau, Council of Agriculture, Executive Yuan (2022) Forestry Statistics. https://goo.gl/4LH2M6/ (accessed April 1, 2022).

Forestry Bureau, Council of Agriculture, Executive Yuan (2022) Wood Price Information System. https://goo.gl/L1TRgU/ (accessed April 1, 2022).

Gagnon, J. L., Jokela, E. J., Moser, W. K., & Huber, D. A. (2003) Dynamic of artificial regeneration gaps within a longleaf pine flatwoods ecosystem. *Forest Ecology and Management*, 172, 133-144.

Guo, Y.-L. (2013) Shade-tolerance of plants and the category of native shade-tolerant tree species in Taiwan. *Forestry Research Newsletter*, 20(4), 36-40.

Haas, S.E., Hooten, M.B., Rizzo, D.M., & Meentemeyer, R.K. (2011) Forest species diversity reduces disease risk in a generalist plant pathogen invasion. *Ecology Letters*, 14, 1108-1116.

IPCC (1996) Climate Change 1995: Impacts, Adaptations and Mitigations of Climate Change: Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. 879pp.

Jactel, H., Brockerhoff, E.G., & Duelli, P. (2005) A test of the biodiversity-stability theory: meta-analysis of tree species diversity effects in insect pest infestations, and re-examination of responsible factors. In: Scherer Lorenzen, M., Korner, C., Schulze, E.-D. (eds.), Forest Diversity and Function: Temperate and Boreal Systems. *Ecological Studies*, vol. 176, Springer, Berlin, Germany, p. 235-261.

Lin, J.-C., Cheng, M.-J., Liu, S.-F., & Lee, K.-C. (2002) Economic benefit evaluation of the potential CO_2 sequestration by the national reforestation program. *Taiwan Journal of Forest Science*, 17(3), 311-321.

Lin, C.-Y., Chiu, C.-M., Lin, S.-T., Chung, C.-H., & Lin, C.-L. (2010) Regeneration development after row thinning in *Cryptomeria Japonica* plantations at Chi-Lan-Shan area. *Quarterly Journal of Chinese Forestry*, 43(2), 233-247.

Lin, J.-C., Liu, I-H., & Tang, S.-C. (2014) The growth performances and carbon stock changes of broadleaf mixed stands. *Quarterly Journal of Forest Research*, 36(1), 57-66.

Lin, J.-C., Hsu, Y.-R., Chan, W.-H., & Wang, P.-J. (2016) Survey and analysis of tree species used in National Leasehold Forest Afforestation. *Quarterly Journal of Chinese Forestry*, 49(3), 261-278.

Liu, W.-Y., Lu, Y.-M., Lin, K.-C. (2009) Measuring the optimal rotation period under carbon price and timber price uncertainty. *Taiwanese Agricultural Economic Review*, 15(1), 1-35.

National Taiwan University Biodiversity Research Center (2006) The Natural Resources and Ecology Database of Taiwan III: Agricultural, Forestry, Fishery and Husbandry. Taipei, Taiwan: Forestry Bureau, Council of Agriculture, Executive Yuan.

Nyland, R. D. (2002) Silviculture: Concepts and Application, 2nd Edition. New York, NY: McGraw-Hill Higher Company. 704pp.

Page, L. M., & Cameron, A. D. (2006) Regeneration dynamics of sitka spruce in artificially created forest gaps. *Forest Ecology and Management*, 221, 260-266.

Pothier, D., & Marcel, P. (2008) Regeneration development under shelter wood in a lowland red spruce-balsam fir stand. *Canadian Journal Forest Research*, 38, 31-39.

Zheng, C.-L., & Shih, Y.-Y. (2006) An analysis of the timber logging cost of leased forestland in Nantou. *Quarterly Journal of Chinese Forestry*, 39(3), 315-327.