frontiers | Frontiers in Forest and Global Change

TYPE Original Research
PUBLISHED 28 September 2023
DOI 10.3389/ffgc.2023.1246992

OPEN ACCESS

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RECEIVED 25 June 2023
ACCEPTED 01 September 2023
PUBLISHED 28 September 2023

CITATION
Lin Y-R and Liu W-Y (2023) Assessment of timber value and carbon credits provided by pure and mixed forests in Taiwan.
Front. For. Glob. Change 6:1246992.
doi: 10.3389/ffgc.2023.1246992

Assessment of timber value and carbon credits provided by pure and mixed forests in Taiwan

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Introduction: Clear-cutting an even-aged pure forest is a conventional forest operation for wood production. However, this type of operation is unsuitable for sustainable management with multiple disadvantages. By contrast, mixed forests are a forestation strategy that accommodates diversity. This study aims to assess and compare the timber value and carbon credits of a pure forest and a mixed forest, which is transformed from a pure forest. Two alternative options in managing plantations of pure forest (with *Cryptomeria japonica*) and mixed forest (with part of *C. japonica* cut and *Cinnamomum camphora* replanted) are evaluated considering both timber value and carbon credits. Scenarios with various harvesting intensities and carbon payments were also considered.

Method: A theoretical model was applied, converting pure forest into mixed forest, then two species are cut or replanted in the second round. By contrast, in the pure forest situation, the setting for the second rotation period is a pure forest for 20 years. The model was applied in a simulation experiment and the study area is Taiwan. The selected tree species are representative and have been chosen for analysis.

Results: This study showed that even-aged pure forests had higher wood sales and lower carbon payments than uneven-aged mixed forests. The net present value from market value would be from –255,403 NTD ha^{-1} to –74,134 NTD ha^{-1} and that from carbon value will be from 156,076 NTD ha^{-1} to 208,937 NTD ha^{-1}.

Discussion: This study showed strategies by which values could be increased during the transition from an even-aged pure forest to a mixed forest. Feasible methods included reducing the costs of reforestation, management, and cutting while increasing carbon prices to increase profits from wood and carbon income. A higher harvesting intensity could contribute to greater production and increase the area available for planting, resulting in greater profits from wood and carbon income.

KEYWORDS

even-aged pure forest, uneven-aged mixed forest, carbon payment, harvesting intensity, non-timber value

1. Introduction

Reforestation brings both direct and indirect benefits involving tangible and intangible values (Ihemezie et al., 2021). The tangible values have quantifiable benefits, such as income from harvested timber. The intangible value associates with ecological benefits, including carbon sequestration, water conservation, land conservation, and protecting wildlife habitats (Jaina et al., 2017). Reforestation also contributes to the stabilization of the microclimatic environment (National Taiwan University Biodiversity Research Center, 2006).

Even-aged stands are normal outcomes of wood production after clear-cutting, as they are usually applied to natural forests or plantations during a rotation period (Bettinger et al., 2016). Re-establishing an even-aged stand is simple and produces wood of similar size. Even-aged management is widespread throughout the world (Germany and Alps, Coppice in south Europe, Canada, United States, etc.). However, cleared land lacks forest protection, and soil erosion easily occurs at the beginning of forest stand renewal (Guo and Yang, 2014; Liu et al., 2018). Wildlife habitats in even-aged pure forests are also destroyed by clear-cutting, causing devastation among animals (Subasinghe et al., 2014; Chaudhary et al., 2016; Dislich et al., 2017). The monoculture of an even-aged pure forest involves low species diversity, which increases its vulnerability to meteorological factors and insect damage (Hartley, 2002; Nyland, 2002; Bowyer, 2006; Carnus et al., 2006; Brockerhoff et al., 2013; Chiu et al., 2014; Moghaddam, 2014). Therefore, most even-aged pure stands do not meet the requirements for sustainable forests (Guo and Yang, 2014). A sustainable forest is a managed ecosystem that balances environmental, economic, and social needs to maintain long-term health and productivity while minimizing negative impacts (Liu et al., 2023). In forest management, numerous strategies can be adopted to reduce the negative effects of large-scale clear-cutting, which is an extensive forestry method that involves completely harvesting vast areas of forest without selective tree removal (Liu and Chuang, 2023). These strategies include gradually removing the upper stories of trees, reducing the area of forest renewal, extending the rotation period, planting forests with more than two species (particularly coniferous and broad-leaved mixed forests), and adopting thinning approaches, which involve selective tree removal to reduce density, allowing remaining trees to grow better. It improves forest health by reducing competition and enhancing growth conditions (Nyland, 2002; Gagnon et al., 2003; Page and Cameron, 2006; Pothier and Marcel, 2008; Lin et al., 2010).

The goal of reforestation has gradually shifted from one of forest production to multiple objectives (O'Hara, 2014; Sharma et al., 2014, 2019), including forest maintenance, biodiversity enhancement, and increasing carbon storage (Pérez-Silos et al., 2021). Various forest-management strategies have been developed to achieve these objectives, including activities like selective harvesting, controlling invasive species, and maintaining ecological balance (Liu et al., 2017, 2021).

Forest maintenance" refers to the ongoing management of a forest to ensure its health and sustainability. It includes activities like selective harvesting, controlling invasive species, and maintaining ecological balance.

Of these strategies, mixed forest management naturally results in biological diversity. Mixed forests are more resistant to various biotic stressors, such as insect damage. They also have greater resistance to abiotic stressors, such as windstorms and droughts (Pardos et al., 2021). Additionally, mixed forests can enhance the esthetic value of landscapes and landscape restoration is the focus of interest in Europe (De Deyn et al., 2004; Jactel et al., 2005; Haas et al., 2011; Lin et al., 2014; Dawud et al., 2016; Coll et al., 2018).

Taiwanese forests are dominated by even-aged pure forests, such as Japanese Cedar (*Cryptomeria japonica*), Cedar (*Cunninghamia lanceolata*), Taiwan Acacia (*Acacia confuse*), Formosan Ash (*Fraxinus griffithii*), Camphor tree (*Cinnamomum camphora*), and Taiwan red pine (*Pinus taiwanensis*) in the early years. Since the 1940s, the reforestation policy has changed to select tree species suitable for the local environment (Chiu, 2010; Ekholm, 2016; Saraev et al., 2019). For example, *Michelia compressa, C. camphora,* and *Calocedrus formosana* were selected from northern Taiwan. The selection of reforestation tree species is mostly determined by the natural conditions, such as the growth rate. In addition, the selection of reforestation tree species also needs to consider the economic value of retrievable timber and non-timber products. Additionally, different tree species should be selected to mitigate the insect damage caused by single-species reforestation. Therefore, the five most common species of coniferous trees and similarly of broad-leaved trees in Taiwan were selected. However, as previously described, the specific species for reforestation should be selected according to the environmental conditions (National Taiwan University Biodiversity Research Center, 2006; Chiu, 2010; Ekholm, 2016; Saraev et al., 2019).

Previous studies focused on the transformation of 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 coniferous and broad-leaved trees are planted in the *Chilanshan* area after row thinning of the *C. japonica* pure forest. This strategy increased economic value and maintained income between the long rotation periods of high-priced cypress stands. Chiu et al. (2014) conducted an experiment using four thinning levels in a *C. formosana* plantation. This study proposed that if the underwood of the stand is well cultivated and appropriate re-thinning is applied to the upper story of *C. formosana*, then the growth and survival of the trees under the forest may be enhanced. This strategy also enhanced the carbon sequestration efficiency of *C. formosana*. Harvesting intensity and carbon payment in their economic analysis were conducted in Nölte et al. (2018), but it is unclear if the findings are consistent with those in Taiwan.

The aim of this study was to estimate the land expectation value of logging an even-aged pure forest replanted with native broadleaved tree species at a fixed harvesting intensity. This study also aims to analyze the land expectation value of cutting at different cutting times and with different harvesting intensities. Carbon payments, in addition to wood sales, were considered as the income of the forest owner. Costs associated with reforestation, management, and logging were included in the model. This study also analyzed critical variables such as logging time, harvesting intensity, and carbon price. Specifically, the effects of these variables on the land expectation value for transforming an even-aged pure forest into uneven-aged mixed forest were determined.

This study assesses an operation model that transforms from an even-aged pure forest into a mixed forest in Taiwan. Analysis in which an even-aged pure forest of *C. japonica* was cut under a fixed harvesting intensity and replanted with the native broad-leaved tree species *C. camphora* were conducted. 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.

2. Materials and methods

2.1. Theoretical model

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

This study mainly focuses on a changed forest phase. The model was applied in a simulation experiment. *Cryptomeria japonica* are cut and *C. camphora* are representative so they were selected for analysis. In the model of converting pure forest into mixed forest, part of the *C. japonica* are cut and *C. 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" to ensure that a pure forest can be formed. The second timber income is not included before the next cutting is conducted. In the present study, an even-aged pure forest (aged T_0) was set as the plantation forest. After T_1, the forest age was $T_0 + T_1$ and was ready for clear-cutting. The costs incurred during T_1 were due to its management and clear-cutting. The income sources during T_1 were carbon payments from carbon sequestration and sales of harvested wood products (HWP). After clear-cutting, the same tree species was reforested until T_2 year. The resulting planted forest was an even-aged, pure forest, aged $T_2 - T_1$. The costs incurred during ($T_2 - T_1$) years are from reforestation and its management. Sources of income are carbon payments from carbon sequestration during ($T_2 - T_1$) years. For a specific area, the land expected value (*LEV*) of an even-aged pure forest was evaluated as follows:

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

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, 1 USD = 31.91 NTD on August 13, 2023) and $c(T)$ is the amount of carbon dioxide sequestration per unit volume of wood at T (ton CO_2/ha); $F(A)$ is the total cost of reforestation 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. Land expected value of transforming from the even-aged pure forest to the mixed forest

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

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

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

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

2.2. Materials and variables

2.2.1. Tree species selection

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

C. camphora is a commercial tree species native to Taiwan. It is widely distributed across areas below an altitude of 1,200 m a.s.l. in northern Taiwan and below 1,800 m a.s.l. in southern Taiwan. The optimal growth altitude for this species is <1,500 m a.s.l. (Feng and Lee, 2009). Lin et al. (2016) reported that the Forestry Bureau personnel responsible for reforestation recommend both *C. japonica* and *C. camphora* for reforestation. Specifically, *C. camphora* is recommended because it has a high survival rate, can be planted in various environments, and has various applications. *Cinnamomum camphora* can thrive in diverse growth environments, including areas with varying levels of sunlight, well-drained soils, and different climatic conditions. Guo (2013) showed that *C. camphora* can tolerate limited light conditions in forests. *Cinnamomum camphora* has applications in timber, essential oil production, camphor extraction, ornamental planting, traditional medicine, insect repellents, wood carving, cultural rituals, agricultural practices, and landscape planting.

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 *C. japonica*, and that in the native broad-leaved forest was *C. camphora*.

2.2.2. Setting of forest age

In this study, the plantation forest was set as a mature forest and the forest age was set at $T_0 = 20$. According to the recommendations for reforestation tree species and the corresponding rotation periods from the *Handbook of the Nationwide Reforestation Program* (Forestry Bureau, Council of Agriculture, Executive Yuan, 1998), the rotation period of *C. camphora* was 30 years and that of *C. japonica* was 20 years. Considering that a few studies have proposed a 30-year rotation period for *C. japonica* (National Taiwan University Biodiversity Research Center, 2006), T_1 was set to 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 for 20 years. In the *LEV* model for transforming the even-aged pure forest into a mixed forest, T_2 was set to 30 years for the formation of the uneven-aged mixed broad-leaved forest. In this study, no specific silvicultural treatment was assumed. A typical rate of cutting of 30% is selected since only part of the forest can be cut.

This study also analyzed and compared the results for various time points of cutting *C. japonica* and then replanting *C. camphora*. Specifically, the results for cutting in the 10th, 15th, and 20th years under 30% harvesting intensity were calculated for all scenarios with cutting and replanting repeated in the 30th year. The forest owner obtained wood income from two cuttings of *C. japonica*. In addition,

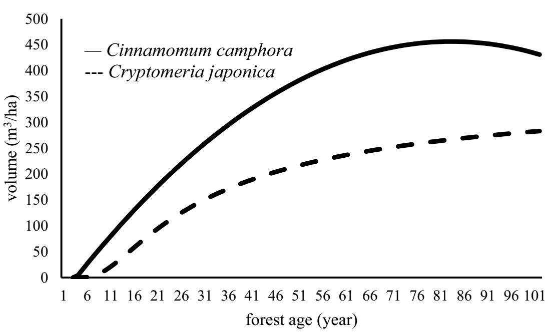

FIGURE 1
Growth curve of the total volumes of *Cinnamomum camphora* (solid line) and *Cryptomeria japonica* (dashed line).

the forest owner obtained annual carbon payments from cutting at the initial time point up to various cutting times and during the growth period of the mixed forest for a total of 30 years of carbon payments.

2.2.3. Volume function (m^3 ha^{-1})

Based on the *C. japonica* growth pattern proposed by Chang et al. (1987), the volume (of stem and branches) of *C. japonica* was estimated using the following formula:

$$V(T) = \exp(5.9027 - 25.6891 / T) \text{ (unit: m}^3 \text{ ha}^{-1}\text{)}.$$

where T refers to forest age. Based on the growth pattern of *C. camphora* proposed by Lin et al. (2002), the estimated volume of *C. camphora* is given by the following formula:

$$V(T) = -18.934 + 11.69\,T - 0.0719\,T^2 \text{ (unit: m}^3 \text{ ha}^{-1}\text{)}.$$

The total volume growth curves of *C. japonica* and *C. camphora* were obtained by calculating the total volume at each forest age based on their growth patterns, as shown in Figure 1. The volume in mixed stands is calculated by the product of volume, area at that age, and percentage of the species per area. We also assume the rate of growth rate in mixed stands is the same of that in pure ones.

2.2.4. Prices of harvested wood products

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). According to Forestry Bureau, Council of Agriculture, Executive Yuan (2023), the demand for various wood materials was roundwood logs = 13%, sawnwood = 23%, wood-based panels = 27%, and pulpwood and wood chips = 37%. The selected species are able to produce these assortments in this proportion in Taiwan and these proportions were used for the breakdown of the HWP in this study.

To determine the price of HWP, this study calculated the average prices of roundwood, panels, and slabs of *C. japonica* for the past 10 years (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022a,b,c), which were 4,341, 10,623, and 5,756 NTD/m^3, respectively. The price of pulpwood and wood chips was set at 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, 2022c). According to the Wood Price Information System of the Forestry Bureau, the average price of *C. camphora* roundwood over the past decade has been 4,341 NTD/m^3.

2.2.5. Costs of planting and management

Under the operational scenario in the present study, reforestation was conducted after clear-cutting the even-aged pure forest. To transform an even-aged pure forest into a mixed forest, native broad-leaved trees were replanted after cutting a coniferous forest. It is noted that the clear-cut is not over the whole forest area, but only in portions or with partial canopy uncovering through thinnings. The cost of reforestation and management should also be considered. In a study by Liu et al. (2009), the cost of reforestation was reduced based on the costs of raising seedlings, outplanting, and weeding. Under the current regulations, the costs of raising seedlings can be estimated. For example, the forest owner must pay 30,000 NTD/ha in the first year of outplanting if certain conditions are met. Regarding outplanting and weeding, there are guidelines on the required manpower and wages according to the Forestry Bureau, Council of Agriculture, Executive Yuan (2002, 2022a,b,c). For example, a 1-year-old planted forest land should be weeded twice a year; each round of weeding requires eight labor days per hectare, and weeding workers need to pay 1,500 NTD each day.

2.2.6. Cutting-related costs

This study examined the operational scenario of clear-cutting an even-aged purely planted forest. An even-aged, pure-planted forest must be clear-cut to facilitate its transformation into a mixed forest. Zheng and Shih (2006) applied a regression analysis to the cost of forest cutting and operational 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 1,493 NTD/m^3.

2.2.7. Carbon payment

Increased greenhouse gas (GHG) emissions are the primary cause of climate change. Forests can absorb and store carbon dioxide, and this forest-based process is crucial for reducing greenhouse gas emissions. This study incorporated carbon payments into the operation scenarios for even-aged pure forests and for transforming them from even-aged pure forests to mixed forests. The effect of transforming 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 (Eggleston et al., 2006 and its refinement Shukla et al., 2019) is given by

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

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

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 dry wood volume, W_T is the transformation coefficient of weight and volume, C_{CO_2} is the carbon dioxide 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 in *C. japonica* and *C. camphora.* Wood volume was transformed into the whole-tree volume, and the specific weight of wood was multiplied to obtain the forest biomass. Subsequently, 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. The C_T values of *C. japonica* and *C. camphora* are 0.4974 and 0.47, respectively. Figure 2 presents the carbon dioxide storage curves for *C. japonica* and *C. camphora*.

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

Based on the Greenhouse Gas Reduction and Management Act of the Environmental Protection Administration, Executive Yuan (2022), this study assumed the carbon payment for carbon dioxide per ton to be 1,500 NTD. This amount is actually paid for plantations that are then cut and timber used.

2.2.8. Discount rate

This study used the *LEV* model to analyze operational scenarios for an even-aged pure forest and the transformation from an 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 a 20-year-old planted forest land were considered. The current preferential interest rate for reforestation loans (1.25%) was used as the discount rate in this study (Bureau of Agricultural Finance, Council of Agriculture, Executive Yuan, 2022).

2.2.9. Scenario setting

In the case of converting an even-aged pure forest into a mixed forest, this simulation study gradually removes *C. 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. The scenario for an even-aged pure forest is shown in Figure 3. The scenario of transformation from an even-aged pure forest to a mixed forest is shown in Figure 4.

3. Results

3.1. Land expected value of even-aged pure forest

This study calculated the per-unit *LEV* model for the 20-year-old even-aged pure forests of *C. japonica* and *C. camphora*. The initial forest age was set at 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 age 20. The forest owner earned wood income when the forest was 30 years old. The forest owner obtained a total worth of 30 years in carbon payments, specifically for the years of forest age 20–30 and 20 years of reforestation. The individual net present value of income from unit wood, net present value per-unit carbon payment, and per-unit *LEV*s of the two pure forests are presented in Table 2. As can be seen, the unit *LEV* from planting *C. camphora* in the even-aged pure forest was 293,249 NTD higher than that from planting *C. japonica*. Specifically, the net present value of the unit wood income of *C. camphora* was 93,064 NTD higher than that of *C. japonica*, and the net present value of the per-unit carbon payment for *C. camphora* was 200,185 NTD higher than that of *C. japonica*.

3.2. Land expected value of transformation from an even-aged pure forest into a mixed forest

The initial forest age was set to 20. The processes of cutting at 30% harvesting intensity and replanting of *C. camphora* were conducted in the 30th year to transform the *C. japonica* forest into a mixed forest. The mixed forest continued to grow for another 20 years, after which cutting and replanting procedures were repeated. The forest owner obtained wood income by cutting the *C. japonica* forest when *C. 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 *C. japonica* forest was aged 20–30 years, and for the 20 years of mixed forest growth, for a total worth of 30 years in carbon payments. Table 3 presents the results for the per-unit *LEV* in the basic scenario of transforming 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.

3.3. Different cutting time

The results for this scenario are presented in Table 4. 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. These later cutting times corresponded to increased reforestation and management costs of *C. japonica* during the cutting period. Moreover, the growth of *C. japonica* increased the cost of cutting; thus, the net present value of per-unit wood income decreased from −124,259 to −125,645 when the cutting time was delayed. The results for the even-aged pure forest indicated that *C. camphora* stored a greater amount of carbon dioxide than did *C. japonica*; thus, the carbon payment for *C. camphora* was higher. However, delayed cutting time reduced the growth time of the replanted *C. camphora*, and the carbon payment was slightly lower. Specifically, the net present value of per-unit carbon payments decreased from 191,317 NTD to 163,985 NTD. Therefore, the per-unit *LEV* decreased from 67,057 to 38,341 NTD when the cutting time was delayed.

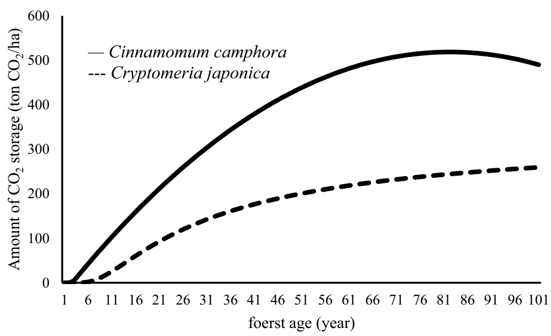

FIGURE 2
Carbon dioxide storage curves of *C. camphora* (solid line) and *C. japonica* (dashed line).

3.4. Different harvesting intensity

In this study, we analyzed and compared *LEV*s harvested at various intensities. The initial *C. japonica* forest age was set at 20. This scenario involved the transformation of a pure forest of the same age into a mixed forest. Three harvesting intensities were analyzed and compared. Specifically, the results were examined for replanting with *C. camphora* after cutting at harvesting intensities of 10, 20, and 40%, where cutting and replanting were repeated in the 30th year for all cases. Based on the harvesting intensity, the forest owner obtained wood income when the *C. japonica* forest was 30 years old and when the mixed forest was 20 years old. Additionally, the owner obtained annual carbon payments for the *C. japonica* forest at forest ages 20–30 and for 20 years of mixed forest growth, for a total of 30 years of carbon payments.

Table 5 shows the results of cutting *C. japonica* and replanting with *C. camphora* under the aforementioned conditions. The net present value of per-unit wood income, net present value of per-unit carbon payment, and per-unit *LEV*s all increased with an increase in harvesting intensity. Increases in cutting intensity resulted in increased costs of cutting *C. japonica* and replanting with

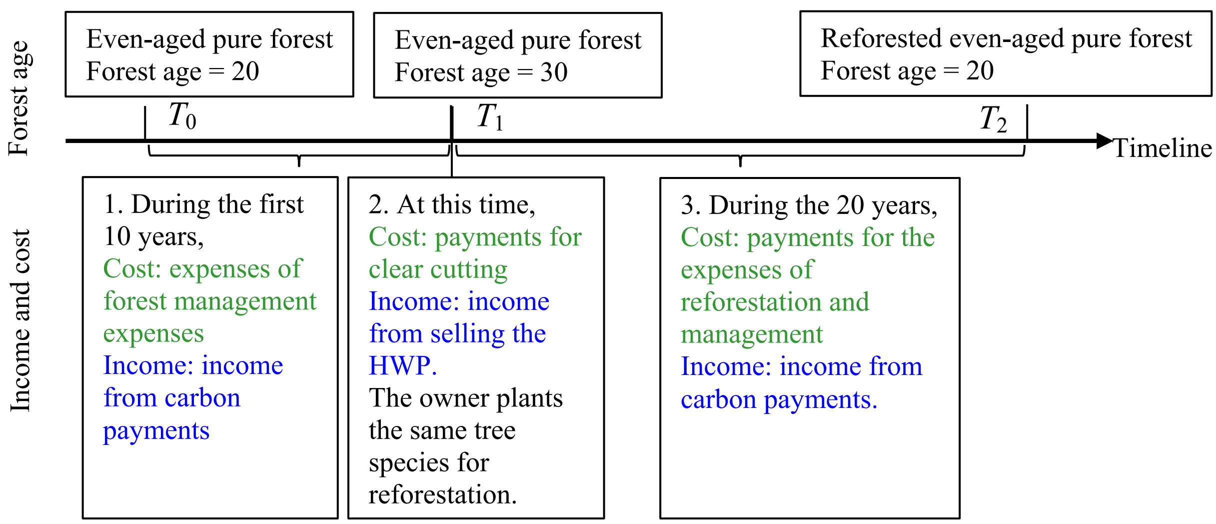

FIGURE 3
Scenario for an even-aged pure forest.

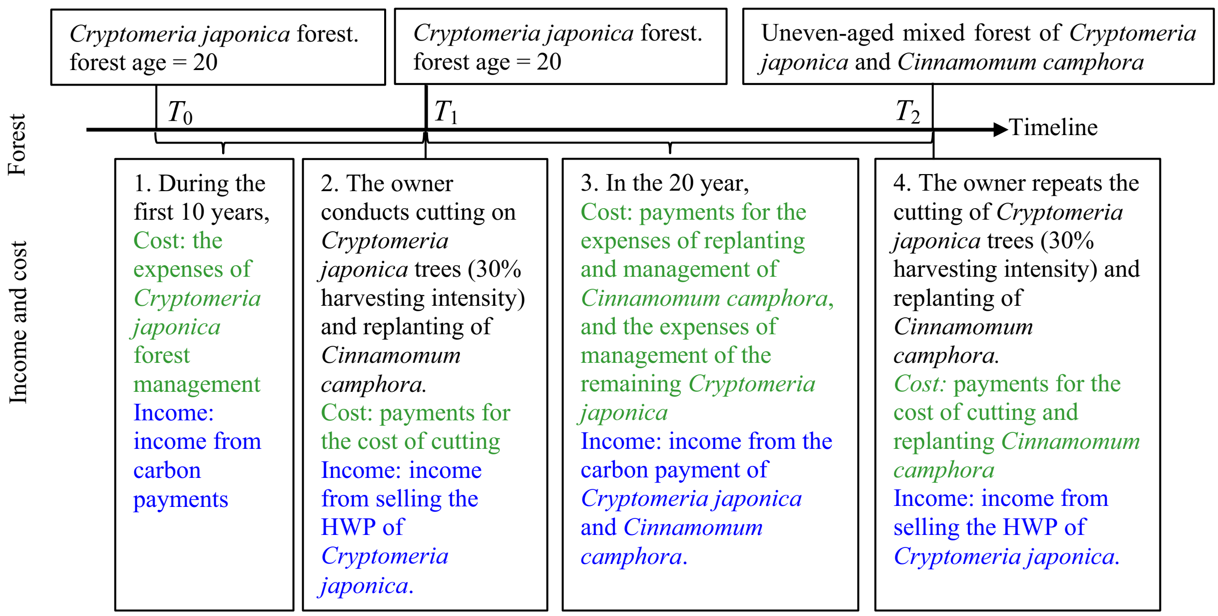

FIGURE 4
Scenario of transforming from an even-aged pure forest into a mixed forest.

TABLE 2 Land expected value (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 *C. japonica*	4,633	173,877	178,510
Even-aged pure forest of *C. camphora*	97,697	374,062	471,759

C. camphora, but increased cutting intensity also corresponded with greater income from greater sales of *C. camphora* HWP. Specifically, the net present value of per-unit wood income increased from −255,403 NTD to −74,134 NTD. The area of replanted *C. camphora* increased with increasing harvesting intensity, contributing to an increase in the net present value per unit carbon payment from 156,076 NTD to 208,937 NTD. Therefore, the per-unit *LEV* increased from −99,327 to 134,804 NTD with an increase in the harvesting intensity.

3.5. Different carbon payments

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

Table 6 presents the results of the study. The net present value of the per-unit carbon payment and per-unit *LEV* increased with an increase in carbon payment. The net present value per unit wood income was fixed at −124,259 NTD. Specifically, the net present value of per-unit carbon payments increased from 64,680 NTD to 637,723 NTD. Accordingly, the per-unit *LEV* gradually increased from −59,579 to 513,464 NTD.

4. Discussion

This study explored an operational model for transforming an even-aged pure forest into a mixed forest. Analysis and comparison of the operation models of the even-aged pure forest indicated that the *LEV* of planted *C. camphora* was higher than that of planted *C. japonica*. Therefore, although the cost of cutting *C. camphora* was higher, the wood income from *C. camphora* was still higher than that from *C. japonica*. The amount of carbon dioxide stored in the growth model of *C. camphora* was also higher than that of *C. japonica*,

TABLE 3 Land expected value 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 *C. camphora* in the 10th and 30th years	−124,259	191,317	67,057

TABLE 4 Land expected value 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 *C. camphora* in the 10th year	−124,259	191,317	67,057
Replanting *C. camphora* in the 15th year	−122,918	178,421	55,503
Replanting *C. camphora* in the 20th year	−125,645	163,985	38,341

indicating that the carbon payment from planting *C. camphora* was higher than that of *C. japonica*.

Although the average unit price for *C. japonica* HWP (5,161 NTD) was higher than that for *C. camphora* (4,023 NTD), the growth curves of *C. japonica* and *C. camphora* (Figure 1) illustrated that the unit stock of *C. camphora* was higher than that of *C. japonica.* Although planting *C. camphora* in the even-aged pure forest involved higher cutting-related costs, the income from *C. camphora* wood was higher than that from *C. japonica* wood. According to the curves of carbon dioxide storage for *C. japonica* and *C. camphora* (see Figure 2), the unit stock of *C. camphora* was higher than that of *C. japonica.* Carbon dioxide storage was calculated based on the growth of *C. camphora*, and the results indicated that the amount of carbon dioxide stored was higher than that stored in *C. japonica.* Additionally, during the 30 years of forest growth, the slope of the carbon dioxide storage curve for *C. camphora* was steeper than that for *C. japonica*. Thus, the carbon payment was higher in the model of planting *C. camphora* in the even-aged pure forest. Accordingly, the per-unit *LEV* of the operational model for planting *C. camphora* in the even-aged pure forest was higher than that for planting *C. japonica*.

An even-aged pure forest was transformed into a mixed forest in the 10th year and replanted with *C. camphora* after *C. japonica* was cut at 30% harvesting intensity. Growth into an unevenly aged coniferous, broad-leaved mixed forest continued until the 30th year, when the same cutting procedure was repeated, yielding a per-unit *LEV* of 67,057 NTD. Later cutting times increased the costs of reforestation, management, and cutting of *C. japonica*. After replanting with *C. camphora*, carbon payments decreased; thus, the per-unit *LEV* decreased. An increase in harvesting intensity resulted in higher income from selling the HWP of *C. japonica* as well as an increased area replanted with *C. camphora*. Carbon payments increased after cutting *C. japonica* and replanting it with *C. camphora*, resulting in an increase in per-unit *LEV*. The result was different from the study conducted by Nölte et al. (2018), which concluded that the carbon payments and *LEV* increased as the harvesting intensity decreased. It is speculated that because Taiwan is a subtropical region, trees grow faster and thinning actually leads to an increase in growth volume.

The operation model of the even-aged pure forest of *C. camphora* maximized the net present value of wood income, which was 97,697 NTD ha^{-1}. For the model transforming an even-aged pure forest into a mixed forest, wood income was not derived from cutting *C. japonica* at 30% harvesting intensity. A total of 51% of the *C. japonica* forest was replanted with *C. camphora*. After deducting related expenses such as reforestation and cutting, the net present value of per unit wood income was only −124,259 NTD ha^{-1}.

The even-aged pure forest of *C. camphora* exhibited the highest net present value of per-unit carbon payment because the unit stock of *C. camphora* was high, and thus correlated with a relatively high amount of carbon dioxide storage. Specifically, the per-unit carbon payment was 374,062 NTD ha^{-1}. To transform an even-aged pure forest into a mixed forest, *C. japonica* was cut and replanted with *C. 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 191,317 NTD ha^{-1}, which was 17,440 NTD ha^{-1} higher than that of the even-aged pure forest of *C. japonica*. In particular, the even-aged pure forest of *C. camphora* exhibited the highest *LEV* (471, 759 NTD ha^{-1}). The net present values of per unit wood income and per unit carbon payments for the even-aged pure forest of *C. camphora* were much higher than those for the mixed forest transformed from an even-aged pure forest.

With respect to harvesting intensity, a greater harvesting intensity resulted in higher production for the *C. japonica* forest, as well as a larger area for planting *C. camphora*, in turn increasing income from wood and carbon payments. A greater harvesting intensity substantially affects forest ecology. Forestry strategies that focus only on increasing the output value of the forestland neglect the initial purpose of transforming an even-aged pure forest into a mixed forest.

In this study, *C. japonica* products were classified as roundwood/logs, sawnwood, wood-based panels, pulpwood, and wood chips, and prices were assigned based on the HPW classifications defined by the FAO, the results of Chen et al. (2012), the Wood Price Information System (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022a,b,c), and the prices in the forestry statistics (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022a,b,c). However, for *C. camphora*, only the log price was published in the wood market price information system, and forestry statistics (Forestry Bureau, Council of Agriculture, Executive Yuan, 2022a,b,c) did not provide

TABLE 5 Land expected value 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

TABLE 6 Land expected value 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 announced by the Bank of Taiwan on April 2, 2022). ** Based on the Greenhouse Reduction and Management Act of the Environmental Protection Administration, Executive Yuan (2022), the carbon price was set to be 1,500 (NTD/ton CO_2).

species-specific production details. Therefore, the price setting for *C. camphora* products could be improved in subsequent studies. Should the government update the information system regarding the market prices of wood products such updated information may benefit decision–making in the forestry sector and serve as a reference for academic research and inquiries.

5. Conclusion

The simulation results of this study explore how to enhance the value of transforming even-aged pure forests into mixed forests. This can be achieved by reducing costs (for reforestation, management, and nurturing) and increasing carbon prices. Increasing the harvesting intensity can enhance the amount of *C. japonica* cutting and the area for planting *C. camphora*, thereby increasing income from timber and carbon payment. The study area is Taiwan, but the methodology can be applied to other areas with different tree species. Our model considers the transition of a mixed forest from a pure forest, incorporating dynamic benefits to align with the current situation. It is noted that an increased harvesting intensity could also inflict severe impacts on forest ecology. If only focused on elevating land productivity, the original intent of altering the even-aged pure forest and creating mixed forests could be lost.

To incentivize forest owners to invest in mixed forests, it is suggested the government establish a reliable carbon trading system and increase the standards and penalties of the Greenhouse Gas Reduction and Management Act. In addition to researching and developing green technologies and strategies for pollution prevention, the government should consider adopting forestry operations as the primary method of reducing carbon emissions. Forest owners can provide carbon storage, which can be sold to meet enterprise and factory demands for carbon emission reduction. 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 encourage enterprises to invest in planting forests, thereby increasing forest coverage and the associated effects of carbon sinks in Taiwan.

In actual situations, the growth rate in mixed stands may not be the same of that in pure ones (Pretzsch et al., 2019). The values may also fluctuate with the prices of raw materials and wages, and forest growth would affect the costs of reforestation, management, and cutting. Additionally, only a 30-year operation period was considered to transform an even-aged pure forest into a mixed forest. In future research, an analysis based on other periods can be conducted to enhance the comprehensiveness of the operational model for a mixed forest. Finally, this study did not consider the proportion of carbon emissions in the scenarios or the use of HWPs. Cutting and wood use affect the carbon emissions from forests. Future studies should consider carbon emissions when determining the actual value of carbon payments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Y-RL analyzed the data and drafted the manuscript. W-YL contributed to the investigation, data analysis, the results, conclusion, and as the corresponding author on their behalf throughout the review, editing, and submission process. All authors contributed to the article and approved the submitted version.

Funding

This work has been supported in part by the National Science and Technology Council, Taiwan, under Grants NSTC 112-2321-B-005-007 and NSTC 112-2628-H-005-003; and the Ministry of Education, Taiwan, under the Higher Education Sprout Project.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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