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A Decision Support System to Assess the Trade-offs Between Timber Production and Ecosystem Services

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ABSTRACT

The 21st century is characterized by a marked increase in public demand to consider the social aspects of forest management, most often as the clear trade-offs between timber production and environmental conservation. In this study, sugi (Cryptomeria japonica D. Don) was estimated forest stand growth. Moreover, five important forest functions, namely, timber production, soil conservation, water resource conservation, carbon storage, and biodiversity conservation were quantitatively assessed, across each forest management unit. The results revealed that the inclusion of constraints related to carbon storage or soil conversation extended the cutting age and increased the area of forest with trees over 120 years of age. The optimized harvest schedules maintained timber production by the regeneration of high-productivity forests, while low-productivity forests on steep slopes were designated for public interest functions. The results proved that the tested approach can successfully take into account the multi-functional nature of forests; in other words, even though timber production decreased, the indicators of certain important public interest functions improved over the study period. This approach can be used to formulate schedules that take into account both national- and local-level regulations and enable forest managers to compare economic performance with environmental gains.

Keywords: *carbon storage, forest multi-functions, forest management plans, harvest schedule, soil erosion*

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INTRODUCTION

Since ancient times, humans and forests have been intricately linked, with forests providing some of the resources, e.g., timber, that human civilizations require to grow. In addition, forests provide diverse ecosystem services, e.g., prevention of soil erosion and run-off, rainwater storage as a water resource, mitigation of floods and purification of polluted water, reduction of atmospheric carbon dioxide levels, and biodiversity preservation (*Schulze et al. 2019*). In a world that is undergoing strong climate change, these functions play important roles in mitigating the effects of natural disasters like floods, tsunamis, and typhoons, among others (*Sato and Shuin 2023; Nakamura et al. 2021; Morimoto et al. 2021*).

As one of the world's leading forest nations, Japan possesses a large amount of forest resources, more specifically, 25 million ha, which corresponds to about 66% of the total land area (*Forestry Agency 2019*). In recent years, both the area and accumulation of planted forests has shown a gradual increase. The sugi (*Cryptomeria japonica* D. Don) dominates the growing stock of planted forests in Japan, and is popular due to its straight shape, good workability, and relatively rapid growth; for this reason, it serves as an excellent building material. Sugi wood is extremely fragrant, weather and insect resistant, soft, lightweight but strong, waterproof and resistant to decay. In Japan, it is favored in both construction work and the production of interior furniture (*Orwa et al. 2009*).

The recent increase in planted forests translates to a large supply of harvested wood, which satisfies the demands of the timber market. Lately, the Japanese government has promoted the stable and efficient supply of domestic timber. However, a forest management plan that only considers timber production is no longer satisfactory in modern society (*Gain and Watanabe 2017*). This is because the contemporary view of timber production includes various environmental metrics, which reflect the reality that forests have many other important functions than solely timber production (*Fujimori 2001*). The increase in Japanese forest resources has been followed by the amendment of the Forest Act and a review of the forest planning system. In Japan, the Forestry Agency stipulates- in detail- matters concerning municipal forest improvement plans. Municipalities are then able to formulate forest improvement plans and are given the authority to set operations, decide on logging, and certify operation plans. Unfortunately, this model is often not adhered to in Japan (*Kakizawa and Kawanishi 2011*).

The United Nations Conference on Environment and Development has called for sustainable forest development, including recognition of the multi-functional nature of forests, to become commonplace across the world. Hence, 'appropriate forest management', which fulfills forest ecosystem services by providing timber in a way that is sustainable for the environment and society, has become an important issue. Investigations of natural recovery and the carbon cycle in planted forests (*Paquette and Messie 2010*), along with considerations of carbon storage in planted forests (*Böttcher and Lindner 2010*), have provided macroscopic insights into forest ecosystem services, such as the improvement of water resource conservation (*Ferraz et al. 2013*).

As economic- and ecology-oriented forest management approaches have conflicting objectives, planning for management that accommodates both economic and ecological sustainability involves certain trade-offs (*Mazziotta et al. 2023*), i.e., the extent of forest land conservation, water resource conservation, wildlife conservation, and timber production. A common optimization method involves allocating ratios to various functions based on the main priorities. Harvest planning models that take into account the multi-functional nature of forests have also been developed. For example, *Eggers et al.* (*2019*) asked experts dealing with the economic, ecological, and social value of forests, as well as professionals involved in reindeer husbandry, to draft a number of indicators for their fields; the researchers then evaluated the answers to compile a comprehensive list of forest values. *Lacerda et al.* (*2023*) integrated the economic and ecological aspects relevant to forestry in mathematical functions to identify the most sustainable forest management approaches for tropical forests. Furthermore, additional studies have formulated forest schedules in ways that comprehensively consider the multi-functional nature of forests over the long-term. In addition to timber production, *Binder* (*2012*) assessed ecosystem services such as non-timber forest products, carbon storage, game species density, and recreational activities, in a bid to optimize public ecological functions on a geographical and spatial scale. H*ernandez et al.* (*2014*) presented a harvest planning model that simultaneously considers the environmental objective of carbon storage as well as various economic objectives.

As mentioned above, various methods can be applied to evaluate the multi-functional nature of forests. Then, decision-makers can select the 'middle way', or the option that allows for gains in both priorities, and thus reconciles the traditional, timber production-focused forestry with the sustainable management of permanent forests via the conservation of biodiversity and other ecological indicators (*Harris and Betts 2023, Kormann et al. 2021*).

In this study, the term 'forest ecosystem service' was defined as including both wood production and public service functions. The term 'public interest function' (*Gibson et al. 2000*) refers to a function of the forest ecosystem that does not involve any direct economic gains, such as the profits associated with timber production. As mentioned above, the term 'public interest function' rather than 'ecosystem service' based on recommendations from previous research (*Gibson et al. 2000*) was used.

The decision analysis system presented in this study was based upon the approach initially published by (*Davis et al. 2001*). In forest management optimization problems, the existence of more than one goal means that a decision-maker must decide which goals will be represented in the objective function and which constraints must be set. A method was proposed for formulating forest management plans that incorporates forest economic, and ecosystem services and then analyzes the relationships between these services. The developed method included the following variables to provide a comprehensive description of forest ecosystem services: timber production (harvest); the difference between expenses and income (profit); the total number of forest operations workers per one day (labor requirements); soil conservation (soil erosion); water resources conservation (water resources provision); carbon storage (carbon storage); and environmental density (area deviation) (*Gibson et al. 2000, Yamaura et al. 2021*). The harvest schedule for a forest management unit (FMU) was first set, which contained information about the thinning, clear-cutting, and replanting of stands during the FMU planning horizon. Next, the values of the seven indicators were estimated under the harvest schedule obtained in the prior step. Maximizing harvest was chosen as the main goal, with maintaining sustainable timber production (scenario 1) set as a constraint. Furthermore, public interest functions regarding carbon storage (scenario 2) and soil erosion (scenario 3) in combination with sustainable timber production, were included as constraints. Mixed integer programming (MIP) was used to derive optimal harvest schedule arrangements for forest management under the three scenarios.

The MIP model was chosen for the following reasons. First, the weighting and summation of multiple indicators under approaches such as multi-objective optimization (*Hernandez et al. 2014*) makes it difficult to grasp the real value of a forest. Second, timber production is a fundamental concern for the forest plan of the Japanese government, as well as a major concern for forest owners because it is directly tied to the economic efficiency of a forest. Third, it has been established that single-objective optimization has the same properties as multi-objective optimization if public interest functions are added as constraints (*Davis et al. 2001*).

MATERIALS AND METHODS

Study Area and Data

This study was conducted from April 2021 to August 2024. The study area, which is situated in the former Atsumi district of Tsuruoka City, Yamagata prefecture, is a privately-owned sugi (*Cryptomeria japonica* D. Don) plantation (7830.11 ha) currently managed by the Atsumi Forest Owners' Cooperative (*Suzuki 2018b*). The study area is located at 38.498 ~ 38.686°N and 139.549 ~ 139.755°E, respectively (**Figure 1a**). 'Excluded 1' is an area of privately-owned artificial cedar forest that represents a designated erosion control forest with protected status under the Japanese Erosion Control Act (**Figure 1b**); thus, this area was excluded from the simulations because it is not suitable for timber production. Stands with site classes 1, 2, and 6 were also excluded because they cover very small areas and stands older than 150 years were excluded because it is difficult to predict the growth of these trees. The area of classes 1, 2, and 6 had a width of less than 1% of the total area, which was 'very small areas.'

The remaining forests areas, i.e., the area calculated by subtracting Exclude 1 and the other non-relevant areas (described above) from all other sugi forests, totaled 6,445 ha, this area mainly involved trees belonging to site classes 3, 4, and 5, with this information determined from the height-age curves built from yield tables (*Suzuki et al. 2018b*).

In Japanese forest, "site classes" refers to the concept that indicates the land productivity of a certain place, or the growth potential of forests. If tree height growth at a certain stand age is the same, it can be considered that the land productivity is the same, therefore, site is used as an indicator of land productivity. The tree height growth curves of Japanese cedar throughout Japan were estimated by previous studies (*Nakajima et al. 2010*).

The data assessed in this study came from several sources. First, forest inventory data and forest planning maps were provided by the Yamagata Prefectural Office. The forest inventory data contain information such as tree species, forest age, and area of each forest stand. This information is collected by the government through surveys such as aerial photo interpretation and the planting history data from forest owners. Based on this information, Japanese prefectures create forest register datasets. Age class data, with the classes split into five-year intervals (5y, 10y, ...) are recorded in the forest inventory. Second, climatic data regarding daily precipitation (4.9 ~ 8.4 mm d^{-1}, the 10-year average), minimum temperature (4.2 ~ 11.1°C), maximum temperature (12.4 ~ 17.4°C), and solar radiation data (11.6 ~ 12.2 MJ m^{-2} d^{-1}) between 2012 to 2021 were obtained from the National Agriculture and Food Research Organization (NARO). these data are available as 1 km-grid values (standard area mesh) based on climatic data from the Japanese Meteorological Agency (JMA) (*Ohno et al. 2016*). The NARO provided data from 1980 (partial data for 2008) to one year in in the future (forecast data). Third, DEM data to a resolution of a 10-m square grid were obtained from the Geospatial Information Authority of Japan.

In this study, the FMU (Forest Management Unit) was used, which was also used in the research by *Suzuki et al.* (*2018a, 2018b*) to investigate how to obtain the most efficient harvesting strategy. The prior research involved a vehicle-based logging system; this was also used in the current study. Each FMU represented an area of 3 ha or more and was created by merging smaller areas within the studied forest; the average slope angle in each FMU was not allowed to exceed 30°. The target FMU in this study was defined as the area obtained by subtracting both 'Exclude 1' and 'Exclude 2' from all the privately-owned cedar forests. The area after the removal of 'Exclude 1' from the privately-owned cedar forests was 6,445 ha, but to calculate the target FMU (3,643 ha), 'Exclude 2' also had to be removed. After the removal of 'Exclude 2', the target FMU area spanned 3,643 ha, (**Figure 1**). Young forests cover a rather small area (**Figure 2**). This observation can be explained by trends in the management of the area, more specifically, the forest industry has slowed down due to falling profitability, and thus, both felling and the resulting reforestation have decreased. Hence, the target FMU show a unimodal age class distribution, with each age class spanning five years, and the 12th age class demonstrating the largest share of trees (**Figure 2**). Concerning the distribution of site classes,

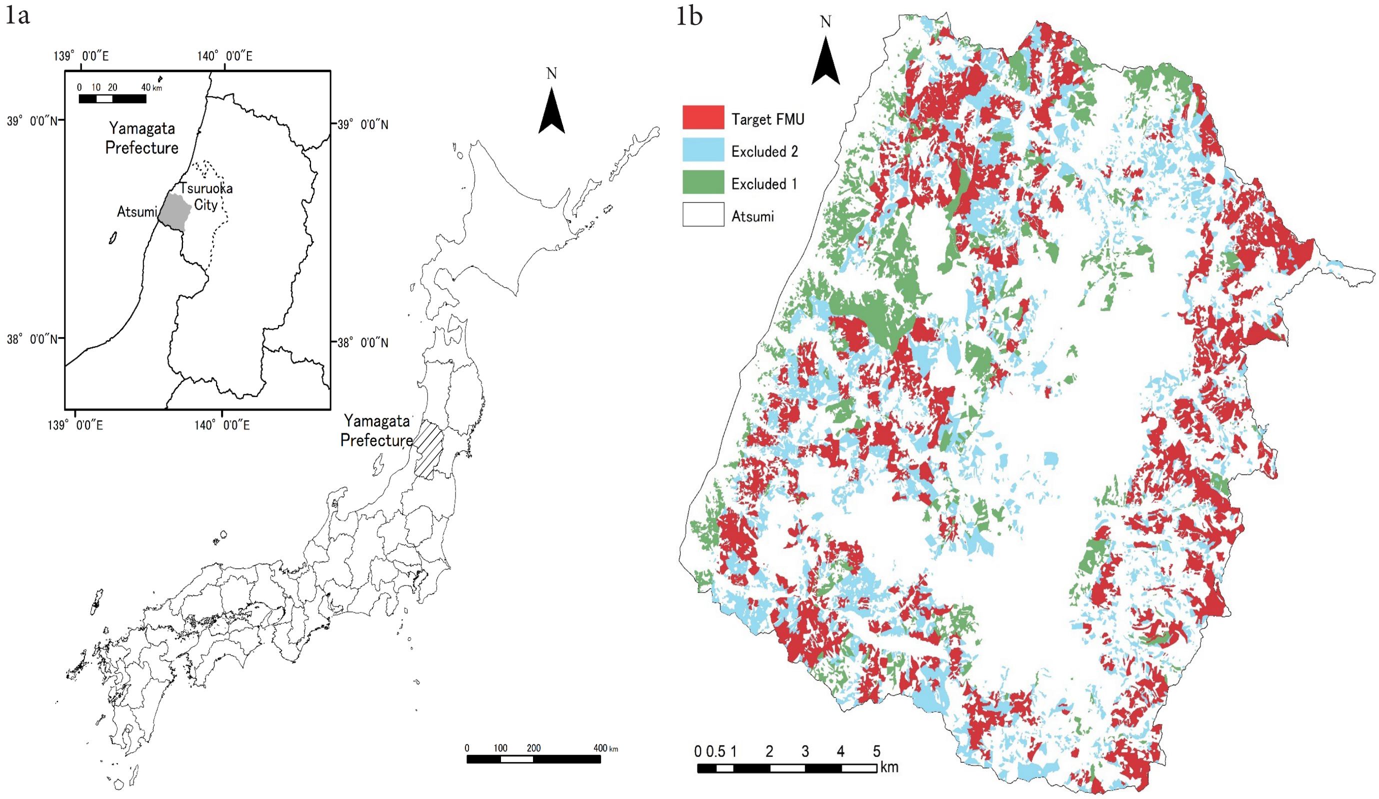

Figure 1. Location of the study area, a privately-owned Japanese cedar (*Cryptomeria japonica* D. Don) plantation in Tsuruoka City, Yamagata prefecture, Japan (a), along with the forest management unit (b).

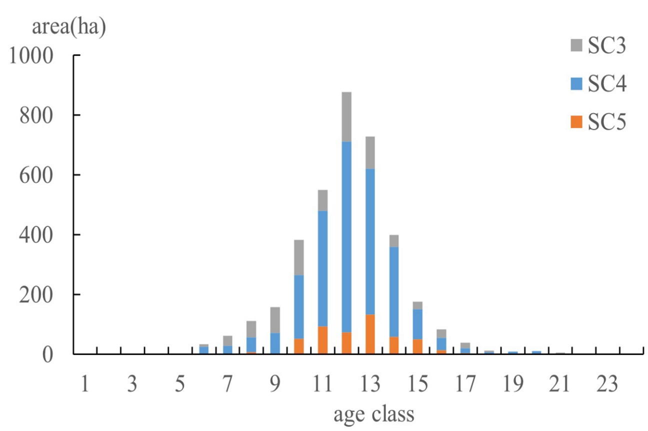

Figure 2. The age class distribution observed in the *Cryptomeria japonica* D. Donplantations of the study area. The age class distribution in the study area, with age classes separated based on ive-year intervals, exhibits a unimodal pattern, with an emphasis on the 12th age class. Regarding the legend, “SC3”, “SC4”, “SC5” in Figure 2 correspond to areas which are classiied as site class 3, site class 4, and site class 5, respectively. The site classes shown in Figure 2 represent differences in forest growth across the FMU, with a curve of tree height growth according to site class provided in *Suzuki et al.* (*2018b*).

half of the study area is classified as site class 4, while forests belonging to site class 5 are mainly distributed across relatively steep areas (*Suzuki et al. 2018b*).

Conceptual Steps

The approach presented in this paper includes two important aspects, namely, the harvest schedule and the forest management plan. The “harvest schedule” provides the specific time points at which timber will be removed from the forest (*Davis et al. 2001*). As such, it represents a schedule for all the silvicultural operations (e.g., thinning, clear-cutting, replanting, and harvesting of timber) that will be carried out within the FMU. The harvest schedule specifies operations based on period, site class, and prescription. Sixteen prescriptions were considered to simulate timber production and public interest functions across stands. The “forest management plan” outlines the comprehensive forest management objectives, direction, and planning horizon for the entire forest area. Maximizing harvest was selected as the primary objective, with maintaining sustainable timber production (scenario 1) set as the constraint. Additional scenarios included other public interest functions, i.e., carbon storage (scenario 2) and soil erosion (scenario 3), as constraints. Next, mixed integer programming was utilized to determine the harvest schedule of each FMU in accordance with the forest management plan.

The flowchart (**Figure 3**) illustrates how forest stand growth was estimated, after which specific indicators, such as harvest, profit, labor requirements, soil erosion, water resources provision, carbon storage, and area deviation, were chosen to evaluate the multifunctional nature of the sugi plantation under 16 prescriptions. Finally, optimal harvest scheduling models were created for the three scenarios described earlier. The following will describe the calculation of these indicators (harvest, profit, labor requirements, soil erosion, water resources provision, carbon storage, and area deviation), this study will also present the three investigated scenarios, along with the corresponding harvest scheduling models. As previous studies (*Suzuki et al. 2018a, Cheng et al. 2023*) have applied calculations across a period of five years, the same approach has been taken. This is considered relevant to the study location because sugi trees do not grow considerably over one year when compared to tropical species of trees. As such, four other indicators were also estimated over a five-year period.

Harvest Forecast

The harvested volume was predicted based on the growth standard rate for sugi and the harvest schedule, as calculated based on what was presented by *Suzuki et al.* (*2018a*). The harvested volume was calculated for each FMU and used as an indicator of timber production.

First, the mean stand height of each age class was predicted based on site class inventory data using the Mitscherlich formula (*Suzuki and Tatsuhara 2016*). Next, stem density and stand volume were calculated using the natural mortality line, which was determined using a stand density control diagram (*Suzuki and Tatsuhara 2016*). However, a new natural mortality should be calculated after each round of thinning based on the new stem density and stand volume. By repeating this process, the stem density for each age and site class was obtained (*Suzuki et al. 2018b*). It should be noted that the study area only included a few young sugi forests. Nevertheless, it is necessary to predict the characteristics of young trees after each reforestation round. For these predictions, the planting density was assumed to be 2,500 stems ha^{-1}. The forest inventory does not include a growth model and represents the current state of the plantation. As such, these data were used as the initial value from which to predict the future state of the forest.

When calculating harvested volume, the Weibull distribution was used to express the diameter distribution, while the relative height-diameter curve (*Suzuki and Tatsuhara 2016*) was used to calculate the stand height by diameter class. The Kunze equation was used as the relative stem profile equation, and timber by diameter class was obtained based on the priority order of log

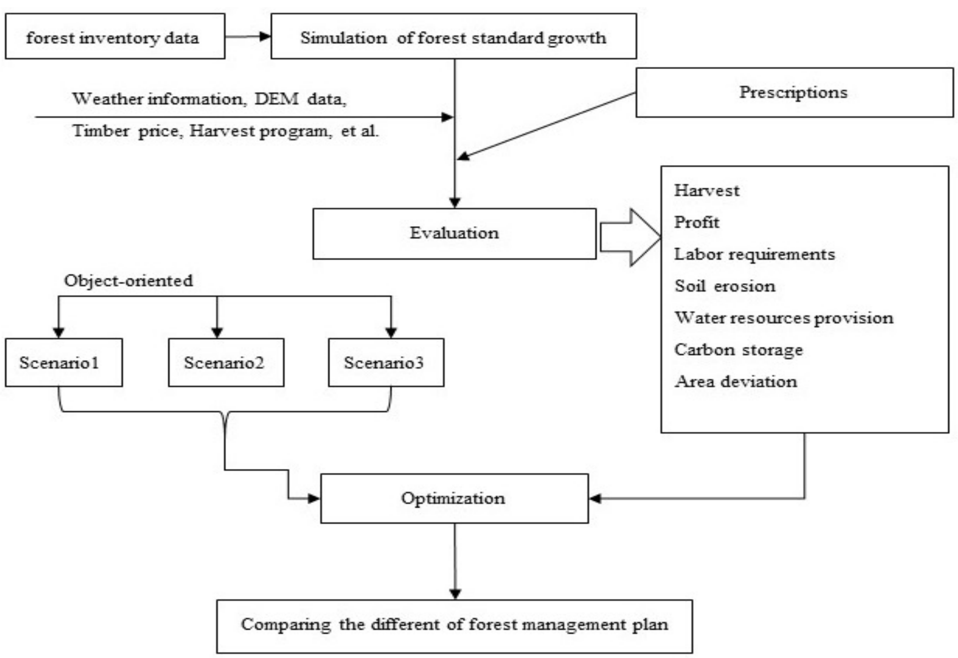

Figure 3. Flowchart for optimizing the harvest schedule of a Japanese cedar plantation. According to the flowchart presented in Figure 3, the values of seven indicators were calculated under 16 prescriptions, after which the management plans for three distinct scenarios were optimized and their performance was compared based on economic and environmental variables.

types (*Suzuki et al. 2018a*).

The harvest schedule considered 15 prescriptions with candidate rotation ages ranging from 50 to 120 years (in increments of 5 years); the final (16^{th}) prescription was one with no clearcutting. Regarding the thinning schedules applied in this study, pre-commercial thinning (thinning rate: 30%) will be performed after 20 and 40 years, while commercial thinning (thinning rate: 25%) was performed at the 70-year mark when the rotation age exceed 75 years.

The profits and labor requirements for various scenarios were calculated based on information about costs, labor requirements, income, expenses, and subsidies. In order to reduce unnecessary calculations, only rotation ages that yielded a positive profit (per ha per year) were considered as possible rotation ages for each FMU. Detailed information about income, labor requirements, and costs was provided in previous study (*Suzuki et al. 2018b*).

Evaluation of the Public Interest Function

FunctionThe public interest function included soil conservation, water resources conservation, carbon storage, and environmental diversity, among other aspects. However, comprehensively evaluating each function separately was outside of the scope of the presented research. Thus, the presented research involved two indicators of public interest, namely, soil erosion and carbon storage.

Soil Conservation

The soil conservation factor involves the prevention of surface layer collapse by the root systems of trees, prevention of surface erosion by understory vegetation and fallen leaves, and prevention of sediment erosion and discharges. Annual soil erosion, calculated via the RUSLE model (soil loss equation), served as the soil conservation indicator. The RUSLE model was developed by the U.S. Department of Agriculture to conserve agricultural land and is based on predictions of the amount of sediment that has been eroded by water and washed away. It represents an improved version of the first USLE model. In both models, six factors were used to evaluate soil erosion per unit area, as shown in Equation 1. The RUSLE model is widely used in soil erosion research because the various coefficients are calculated independently and can thus be individually adjusted and improved according to the research objective and data sources (*Alewell et al. 2019*).

$$A=R \cdot K \cdot L \cdot S \cdot P \cdot C \tag{1}$$

where:

A is annual average soil erosion (t ha^{-1} yr^{-1})
R represents the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1})
K is the soil erodibility factor (t ha^{-1} MJ^{-1} mm^{-1})
L is the slope length factor (dimensionless quantity)
S is the slope steepness factor (dimensionless quantity)
P is the soil conservation or prevention practices factor (dimensionless quantity)
C represents the land cover and management factor (dimensionless quantity).

The rainfall-runoff erosivity factor (R) was calculated using Equation 2 (*Wischmeier and Smith 1978*) based on the monthly and annual rainfall values extracted from the agro-meteorological grid data. An estimate for each unit was then obtained through ArcMap ver. 10.4 (ESRI, Redlands, CA).

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5lg\frac{Pi^2}{P_a}-0.8188\right)} \tag{2}$$

where Pi is monthly rainfall (mm) and P_a is annual rainfall (mm).

The slope length and slope steepness factors (L and S) describe how the terrain of a site influences soil erosion. The two factors were calculated via Equations 3 and 4 based on DEM data from ArcMap ver. 10.4 (*Suzuki and Tatsuhara 2016*).

$$L = \left(\frac{l \cdot cos\theta}{22.13}\right)^m \tag{3}$$

$$S = \begin{cases} 10.80sin\theta + 0.03; \leq 5° \\ 16.80sin\theta - 0.50; 5° < \leq 10° \\ 21.91sin\theta - 0.96; > 10° \end{cases} \tag{4}$$

where l is the slope length (m), θ is the slope angle (°), and m is a parameter related to percent slope (m is 0.5 if the slope angle is ≥2.56°, 0.4 if the slope angle is between 1.72° - 2.86°, 0.3 if the slope angle is between 0.57° - 1.72°, and 0.2 if the slope degree is <0.57°). The soil erodibility factor (K) describes soil properties. It is statistically related to soil properties that influence water-induced erosion. These include characteristics affecting infiltration rate, permeability, and total water-holding capacity, as well as those impacting the soil's susceptibility to dispersion, splashing, abrasion, and transport by rainfall and runoff (*Alewell et al. 2019*). Because the soil in the study area is mainly fine-grained brown forest soil, it was set at 0.028 (*Imai 2007*). The soil conservation or prevention practices factor (P) is related to the effects of land use classification. This area is consistently classified as forest, so the factor was set to 1 in this study.

The land cover and management factor (C) presents crop cover and is estimated from the condition of crops that are planted in the study area. When calculating this factor, land cover conditions are generally estimated by analyzing existing aerial photographs or conducting field surveys (*Alewell et al. 2019*). A factor that can change noticeably over time is the state of the forest. For instance, Equations 5, 6, and 7 (*Miura et al. 2015, Kuusk et al. 2004, Komatsu et al. 2014*) take into account changes in forest conditions. However, the land cover and management factor (C) was difficult to calculate using the method described above from the available dataset.Therefore, it was estimated indirectly using Eq. 5 (*Miura et al. 2015*).

$$C= exp(-0.051C_f) \tag{5}$$

where C_f is the forest coverage rate (%).

The forest coverage rate C_f was obtained via Equation 6, which describes the relationship between leaf vertical degree and leaf area index (*Kuusk et al. 2004*). The leaves of plants were assumed to be spherical and randomly distributed, as such, β was set to 57.3°.

$$C_f=1-e^{-L_{AI}/(2cos\beta)} \tag{6}$$

Where L_{AI} is leaf area index and β is the view zenith angle. The leaf area index was estimated from the stem density and mean diameter at breast height (DBH), with a_{ref} set as 1.40 cm² and s set as 1.55 as shown in Equation (7) (*Komatsu et al. 2014*).

$$L_{AI}=0.157N{\cdot}a_{ref}{\cdot}d^s \tag{7}$$

Where N describes stem density (stems ha^{-1}), d is average DBH (cm), while a_{ref} and s are parameters (described above).

Water resource conservation

Water resource conservation describes the ability of forests to mitigate flooding when a strong rain event occurs, as well as participate in water storage (including stable discharge into rivers) and water purification. In this study, annual water resources provision, which essentially describes the water balance, was chosen as the indicator for water resource conservation. In the case of forests, rainfall predominantly contributes to water inflows, while outflows mainly comprise canopy transpiration, rainfall interception, and forest floor evapotranspiration. The annual water resources provision, Q, was calculated via Equation 8 (*Yamaura et al. 2021*).

$$Q=P-E_t-E_i-E_f \tag{8}$$

where P is rainfall
E_t is canopy transpiration
E_i is rainfall interception and
E_f describes forest floor evaporation

Canopy transpiration, rainfall interception, and floor evaporation were calculated using the following equations, which are based on the methods of *Komatsu et al.* (*2014*) and *Komatsu* (*2020*). Canopy transpiration describes the process through which trees release water vapor to the atmosphere and was estimated using a simplified version of the Penman-Monteith equation (9).

$$E_t=p{\cdot}C_p{\cdot}G_c{\cdot}D/(\gamma{\cdot}\lambda) \tag{9}$$

where p is air density, C_p is the specific heat of the air, G_c is canopy conductance, D represents daytime vapor pressure deficit, γ is the psychometric constant, λ describes the latent heat of water vaporization.

When D is 1.0 kPa, and G_c is the product of a function that describes the response to weather factors.

$$G_c = G_{cref} \cdot f(D)g \cdot (Rs) \cdot h(T) \tag{10}$$

$$G_{cref} = 0.000157 \cdot N \cdot a_{ref} \cdot d^s \tag{11}$$

$$f(D) = 1.00 - 0.556ln(D) \tag{12}$$

$$g(Rs) = min\left[\left(\frac{Rs}{600}\right)^{0.284}, 1.00\right] \tag{13}$$

$$h(T) = max\,(0.00, min\{(T + 8.74)/24.6, 1.00\}) \tag{14}$$

$$D = e_s(T) - e_s(T_n) \tag{15}$$

$$T = (T_x + T_n)/2 + (T_x - T_n)/(3) \tag{16}$$

where Rs is daytime solar radiation, T_x is daytime maximum temperature, T_n is daytime minimum temperature, and e_s describes the saturated vapor pressure.

Of the functions as shown in equation (10) to (16) presented by previous studies (*Jarvis 1976; Oren et al. 1999; Komatsu et al. 2014 ; Park et al. 2021*), g(Rs) is the function that was used to calculate the coefficient for correcting canopy conductance by solar radiation, while the f(D) function was used to calculate the coefficient for correcting canopy conductance by atmospheric pressure. Moreover, the h(T) function was used to calculate the coefficient for correcting canopy conductance by temperature.

Rainfall interception, E_i, was estimated from rainfall P using Equation 17 (*Komatsu et al. 2014*).

$$Ei=0.308\{1- exp(0.000880N)\}\cdot P \quad (17)$$

Forest floor evapotranspiration describes the evaporation of water from the forest floor and was estimated using the Priestley-Taylor equation (Equation 18-20).

$$E_f=0.75\Delta\cdot R_n\cdot exp\ (-0.56L_{AI})/(\Delta+\lambda) \quad (18)$$

$$R_n=Rs\cdot min(0.60+0.067L_{AI},0.80) \quad (19)$$

$$L_{AI}=0.157N\cdot a_{ref}\cdot d^s \quad (20)$$

where Δ describes the slope of the vapor saturation curve. N describes stem density (stems ha^{-1}), d is average DBH (cm), while a_{ref} and s are parameters as shown in equation (7).

Carbon Storage

Carbon storage represents a significant mechanism for mitigating climate change, with this factor describing the amount of carbon that can be stored as the biomass present in a forest. Carbon storage was calculated using an equation related to forest stem volume (*Forestry and Forest Products Research Institute 2021*).

$$\Delta C=Ca - Ce \quad (21)$$

$$C_i=V_i\cdot\rho\cdot k\cdot(1+b)\cdot r \qquad i= a \text{ or } e \quad (22)$$

where Ca is the carbon that is considered to be absorbed during growth, Ce is carbon emitted from logging operations, V is the volume of lumber, ρ describes basic wood density, k is the expansion factor, b is the root-shoot ratio, and r is the carbon fraction per dry weight.

The research focused on the sugi forests, hence, ρ was set to 0.314 t m^{-3}, k was set to 1.57 for trees 20 years of age or younger and 1.23 for trees over 20 years of age, b was set to 0.25, and r was set to 0.5 based on the previous studies (*Shin et al 2014; IPCC 2006*).

Environmental Diversity

Under the Montreal Process for the conservation and sustainable management of temperate and boreal forests, conservation of biodiversity is listed as criterion 1, with forest area by age class one of the presented indicators. Therefore, the environmental diversity of the plantation was evaluated based on age class distribution in this study. It was hypothesized that a normal forest age class distribution would result in the highest environmental diversity because it has been stated that the presence of forests of various ages is important for biodiversity (*The Montréal Process 2015*). For example, relatively young forests provide the feeding grounds in which predatory birds can hunt small animals. Relatively old forests, on the other hand, will show a complex stand structure and the increased possibility of invasion by broad-leaved trees. Thus, it was realized that quantifying the proportions of various forest types (for example, young vs. old-growth) was necessary to reliably evaluate environmental diversity. For this reason, new age groups were defined: age classes 1-3 now represent the 1st age group; age classes 4-6 belong to the 2nd age group; age classes 7-9 fall under the 3rd age group; age classes 10-12 represent the 4th age group; age classes 13-15 fall under the 5th age group; age classes 16-18 belong to the 6th age group; and age classes 19 and above represent the 7th age group. This new definition of the age groups resulted in a total of seven groups. Next, the deviation between each age group area and the normal forest age group area was calculated, after which all of these values were summed to provide an absolute value.

In the study area, forest areas less than 20 ha are allowed to be felled. As Japanese forestry is characterized by a large share of small-scale forest owners (*Chubu Regional Forest Office 2023*), it can be assumed that adjacency constraints do not have to be considered when assessing forest ecosystem services. Therefore, the adjacency constraints were not considered when calculating the public interest functions for each period.

In this study, the following limitations might arise in the analysis due to the exclusion of adjacent constraints. In particular, when adjacent forest stands are harvested simultaneously, this assumption may underestimate habitat fragmentation (*Zhu et al. 2008*), soil erosion (*Eliot et al. 2008*), and landscape impacts (*Gustafson et al. 2007*), among other effects, and this should be noted. Such limitations should be taken into consideration when considering forest management based on the methodology of this study (Equation 23).

$$S = S_t/7 \quad (23)$$

$$B = \sum_{i=1}^{7}|S_i - S| \quad (24)$$

where B is area deviation;
S is normal forest age group area

St is the total forest area, and
Si is the area of each age group

Formulation of a Long-term Harvest Scheduling Model

A long-term harvest scheduling model was formulated to simulate and understand how forest management plans with varying priorities would modify the harvest schedule. The planning horizon was set to 120 years and included 24 five-year periods. Mixed integer programming was applied to formulate the long-term harvest scheduling model, which would assign only one prescription to each FMU. The three tested scenarios were as follows:

Scenario 1: Sole focus is on sustainable timber production (economic gains).
Scenario 2: Both sustainable timber production and carbon storage are considered when planning operations.
Scenario 3: Both sustainable timber production and soil erosion are considered when planning operations.

In this study, the terrain, i.e., slope, was assumed to be stable and unchanging. The average values of weather data from the past 10 years were calculated and assumed that these values would remain constant into the future. This decision was made because various researchers have stated the difficulty of predicting the future climate over a long-term period. Even with improvements in model resolution and complexity, the range of predictions (i.e., the extent of uncertainty) has not narrowed for some key variables (*Knutti and Sedláček 2012*). For example, variables such as precipitation may still involve substantial uncertainty despite advancements in modeling (*Hawkins and Sutton 2009, Lehner et al. 2020*), and fundamentally unquantifiable uncertainties (*Deser et al. 2012*) continue to hinder long-term climate projections. As shown in the constraint equations 37 to 44 for scenarios 2 and 3, soil erosion and carbon storage were considered as public interest functions, but water resources provision and environmental diversity were not incorporated into the constraint equations. This decision was made because water resources provision and environmental diversity, when compared to soil erosion and carbon storage, will show relatively small fluctuations under the harvest schedules assumed in this study. However, water resources provision and environmental diversity are also important public interest functions. Therefore, to confirm that the provided harvest schedules would have a minimal negative impact on these functions, the optimization results have been described in detail as well as visualized them graphically. In this way, water resources provision and environmental diversity serve as reference information for confirming how harvest schedules that consider economic performance can also adhere to certain public interest functions.

In this study, carbon storage was used as a constraint to determine how setting a pre-determined carbon budget would affect the optimized harvest schedule across the entire study site. By visualizing the carbon stock of the entire study site, the local effects of changes in the carbon stock can be visualized relative to the entire region. Furthermore, in the perspective of stakeholders, such as residents and governments, changes in the carbon balance that differ from quarter to quarter can be acceptable as long as the effect on the total carbon stock in the region is small.

To ensure sustainable forest management over the planning horizon, labor requirements and harvested volumes must remain stable. The fact that the area currently shows a unimodal age class distribution will safeguard against rapid harvesting in earlier periods. More specifically, some fluctuation was permitted during the first 10 periods (called the transition period), while less fluctuation was permitted in later periods (called the stable period) to ensure high stability (*Suzuki et al. 2018b*). The fluctuation tolerance for minimum labor requirements and harvest volumes was set as <+30% during the transition periods, and ±10% during the stable periods. The same fluctuation limits were applied for carbon storage (scenario 2). The fluctuation tolerance for the soil erosion scenario (scenario 3) was set as >-50% and lower than the maximum soil erosion value during the transition period, and ±10% during the stable periods. The formulated harvest scheduling model is presented below.

Objective

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} V_{i,j,t}\, x_{i,j} max \tag{25}$$

Subject to

$$\sum_{i=1}\sum_{j=1} L_{i,j,t} x_{i,j} \leq (1 + r_{trans}) LStandard \quad \forall t \in \{1, \cdots, t_s\} \tag{26}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t} x_{i,j} \geq LStart \quad \forall t \in \{1, \cdots, t_s\} \tag{27}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t} x_{i,j} \leq (1 + r_{trans})\ VStandard \quad \forall t \in \{1, \cdots, t_s\} \tag{28}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t} x_{i,j} \geq VStart \quad \forall t \in \{1, \cdots, t_s\} \tag{29}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \le (1+r_{stable})LStandard \ \forall t \in \{t_s,\cdots,T\} \quad (30)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}x_{i,j} \ge (1-r_{stable})LStandard \ \forall t \in \{t_s,\cdots,T\} \quad (31)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \le (1+r_{stable})\ VStandard \ \forall t \in \{t_s,\cdots,T\} \quad (32)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,t}x_{i,j} \ge (1-r_{stable})\ VStandard \ \forall t \in \{t_s,\cdots,T\} \quad (33)$$

$$\sum_{j=1}^{J} x_{i,j} = 1 \qquad \forall i \quad (34)$$

$$y_{i,j} \ge x_{i,j} \qquad \forall i,j \quad (35)$$

$$x_{i,j}, y_{i,j} \in \{0,1\} \qquad \forall i,j \quad (36)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} C_{i,j,t}x_{i,j} \le (1+r_{trans})CStandard \ \forall t \in \{1,\cdots,t_s\} \quad (37)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} C_{i,j,t}x_{i,j} \ge CStart \qquad \forall t \in \{1,\cdots,t_s\} \quad (38)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} C_{i,j,t}x_{i,j} \le (1+r_{stable})CStandard \ \forall t \in \{t_s,\cdots,T\} \quad (39)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} C_{i,j,t}x_{i,j} \ge (1-r_{stable})CStandard \ \forall t \in \{t_s,\cdots,T\} \quad (40)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_{i,j,t}x_{i,j} \ge (1+r_{trans})AStandard \ \forall t \in \{1,\cdots,t_s\} \quad (41)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_{i,j,t}x_{i,j} \le AStart \qquad \forall t \in \{1,\cdots,t_s\} \quad (42)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_{i,j,t}x_{i,j} \le (1+r_{stable})AStandard \ \forall t \in \{t_s,\cdots,T\} \quad (43)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_{i,j,t}x_{i,j} \ge (1-r_{stable})AStandard \ \forall t \in \{t_s,\cdots,T\} \quad (44)$$

where *LStandard* represents the sustainable labor requirement standard, *VStandard* represents the sustainable timber standard, *CStandard* is the sustainable carbon storage standard, *AStandard* is the sustainable soil erosion standard, *LStart* is the minimum labor requirement in transition periods, *VStart* is the minimum amount of harvested timber during transition periods, *CStart* is the minimum carbon storage during transition periods; *AStart* is the maximum soil erosion during transition periods, I is the total number of Target FMU, *J* is the total number of prescriptions, *T* is the total number of periods, $L_{i,j,t}$ is the labor requirement when prescription *j* is applied to FMU *i* in period *t*, $V_{i,j,t}$ is the harvested volume when prescription *j* is applied to FMU *i* in period *t*, $C_{i,j,t}$ represents the carbon storage when prescription *j* is applied to FMU *i* in period *t*, $A_{i,j,t}$ represents soil erosion when prescription *j* is applied to FMU *i* in period *t*; $x_{i,j}$ is 1 when prescription *j* is applied to FMU *i*, and otherwise 0, $y_{i,j}$ is 1 when prescription *j* is a candidate for FMU *i*, and otherwise 0, r_{trans} describes the fluctuation tolerances during the transition periods, and r_{stable} describes the fluctuation tolerances during the stable periods.

Equation 25 represents the maximization of the total harvested volume over the 120-year planning horizon. Equations 26 to 33 impose constraints related to labor and harvesting activities. Equation 34 ensures that only one prescription is applied to each Forest Management Unit (FMU), while Equation 35 defines which prescriptions are available for each FMU. Equation 36 specifies that the binary variables must take a value of either 0 or 1. Equations 37 to 40 introduce constraints on carbon storage, which are applied exclusively in Scenario 2. Similarly, Equations 41 to 44 define constraints on soil erosion, applied only in Scenario 3.

Harvested volume, labor requirements, profits, carbon storage, and soil erosion were calculated for each FMU under candidate prescriptions as described in the previous sections, and then input into the model. Next, the mixed integer programming problems were solved using IBM ILOG CPLEX Optimization Studio ver. 22.1 (IBM, Armonk, NY) (**Table 1**). In order to clarify the trade-offs between forest economic and ecosystem services, the harvest schedule was optimized under a series of different constraints. Based on the long-term harvest scheduling model, first, four new parameters were input into the

Table 1. Values for the parameters involved in the long-term harvest scheduling model for Japanese Cedar (*Paramet japonica*).

Parameter	Value	Unit
LStart	10,000	person days
VStart	100,000	m^3
CStart	330,000	t
AStart	15,000	t $year^{-1}$
I	657	
J	16	
T	24	period
r_{trans}	0.3 or 0.5	
r_{stable}	0.1	

carbon storage (*CStart*) and soil erosion (*AStart*), constraints within the long-term harvest schedule model; more specifically, *CStart* gradually decreased from 330,000 to 10,000, whereas *AStart* gradually decreased from 15,000 to 1,000. Next, the long-term harvest schedule model was optimized under the various constraints. The total harvested volume of lumber, along with soil erosion and carbon storage, were charted throughout the 120-year planning horizon (24 periods), after which a curve was fit to the results to determine the trade-off relationship.

RESULTS AND DISCUSSION

The results of the long-term harvest schedule model were unique for the three separate scenarios. For instance, scenario 1, which solely focused on the sustainable production of timber, showed a decreased in harvested volume and labor requirements over the 24 five-year periods (**Table 2**). The trends over the same period in scenarios 2 and 3 were a marked decrease in harvested volume and soil erosion per ha and an increase in total carbon storage, respectively. The three scenarios were characterized by different proportions of each site class (**Figure 4**). The proportion of site class 3 across the Target Forest Management Unit (FMU) remained relatively stable under all three scenarios. In contrast, the share of site class 5 areas showed scenario-specific differences; for instance, the proportions of site class 5 areas sharply decreased when harvested volume and soil erosion decreased, but the share of site class 5 areas grew when carbon storage increased. Scenario 1 had a large share of Target FMU that were assigned relatively early rotation age prescriptions (50 ~ 90 years), while Scenarios 2 and 3 included Target FMU with relatively late rotation age prescriptions (90 ~ 120 years) along with a considerable share of areas designated as no clear-cutting zones. This trend of areas designated as no clear-cutting zones was particularly noticeable in Scenario 3 (**Figure 5**).

Scenario 1 involved the maximization of harvested volumes without any consideration of public interest functions, while Scenarios 2 and 3 considered public interest functions (soil erosion and carbon storage, respectively) in addition to the economic perspective (**Figure 6**). As such, scenarios 2 and 3 when compared to scenario 1 showed decreases in the harvested volume, profits, and labor requirements, along with decreases in soil erosion and area deviation and increases in water

Table 2. Standard values for each scenario.

Standard	Scenario 1	Scenario 2	Scenario 3
Harvest (104 m^3 period^{-1})	13.47	12.12	11.16
Labor requirements (person days period^{-1})	43264.00	37286.00	33901.00

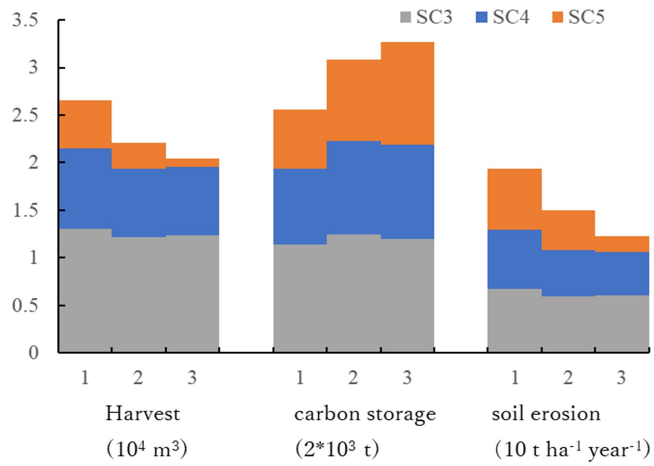

Figure 4. Total harvested volume (m^3), total carbon storage (t), and total soil erosion (t ha^{-1} yr^{-1}) at the end of the 120-year planning horizon (24 five-year periods). The figure presents the values of certain indicators (harvested volume, carbon storage, soil erosion) under different scenarios at the conclusion of the 120-year planning horizon. The numbers “1”, “2”, and “3” on the x-axis represent “scenario 1”, “scenario 2”, and “scenario 3”, respectively. Moreover, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

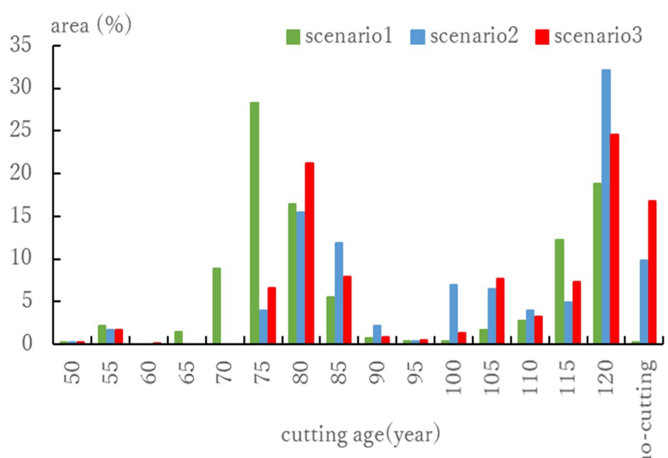

Figure 5. The share of various silvicultural prescriptions (in % of area) across the 120-year period for the three different scenarios. The age of trees at the selected silvicultural prescription (cutting) is shown on the x-axis, while the share of the total area assigned to the prescription is shown on the y-axis.

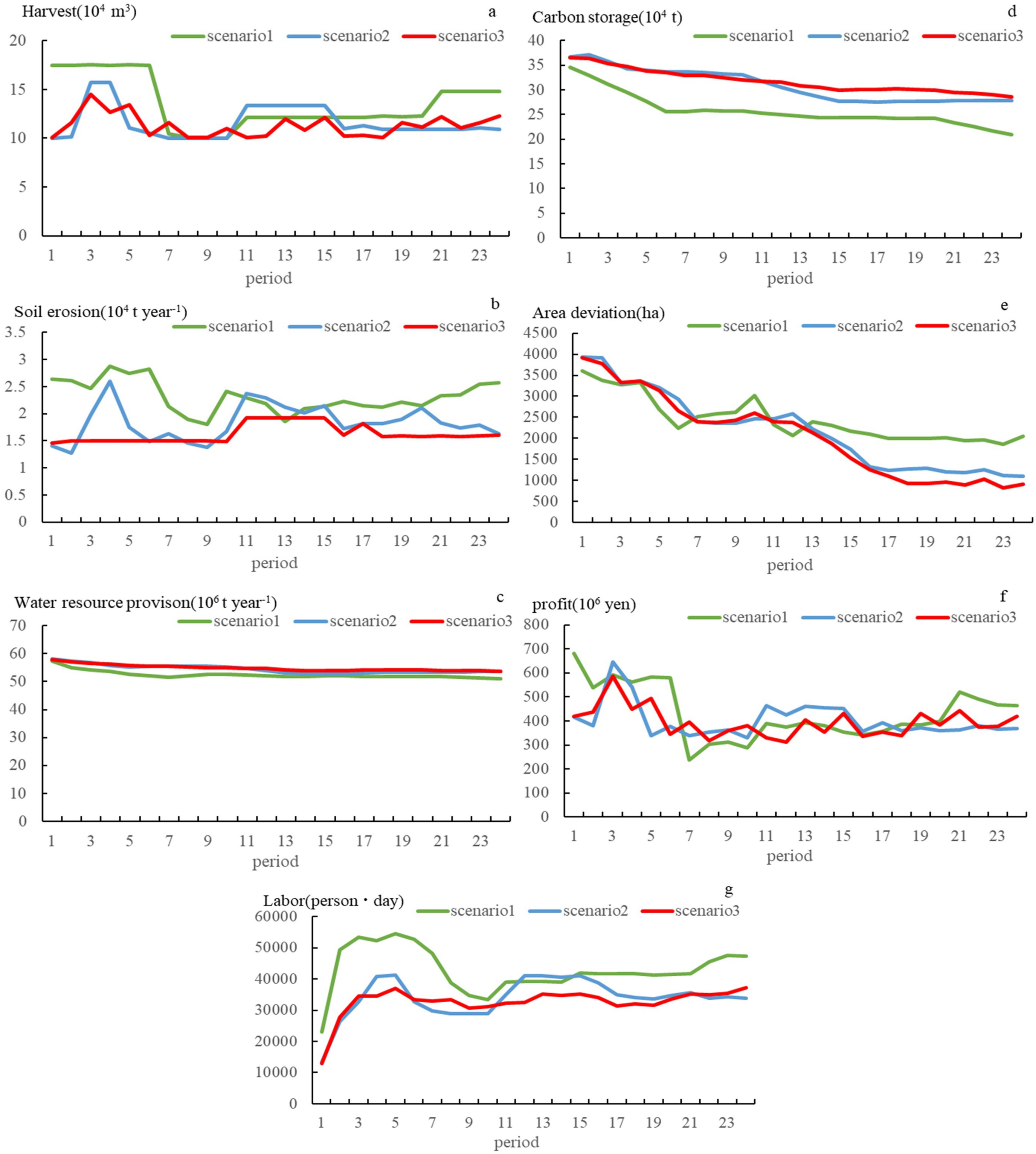

Figure 6. Run charts of a) harvested volume, b) soil erosion, c) water resource conservation, d) carbon storage, e) area deviation, f) profits, and g) labor requirements for the three scenarios throughout the simulated 120-year time horizon.

resource conservation and carbon storage. In other words, the designation of some Target FMU as no clear-cutting zones for the provision forest ecosystem services ultimately decreased timber production; and indicated a trade-off between timber production and public interest functions in the study area. Profit is reported only as a result, as a reference to the output of the optimization. As such, in this study, profit is not used directly in the optimization and is not calculated as a net present value (NPV) without considering discount rates whose variability is difficult to predict.

The charts showed varying trends in the seven indicators across the 120-year planning horizon (24 five-year periods). Moreover, by reconfiguring the parameters of the applied constraints (**Table 2**), the information needed to build a trade-off curve was obtained. It was possible to quantify the trade-off between timber production and the two distinct public interest functions (**Figure 7**). More specifically, when *CStart* was changed from 330,000 to 320,000, total carbon storage decreased by approximately 300,000 t and total harvested volume increased by 100,000 m^3 during the planning horizon. When CStart was changed from 300,000 to 290,000, total carbon storage fell by approximately 100,000 tons and total harvested volume grew by 20,000 m^3 during the planning horizon. Furthermore, changing *AStart* from 15,000 to16,000 resulted in increased total soil erosion (by approximately 100,000 t) and increased total harvested volume (100,000 m^3) during the planning horizon. When *AStart* was changed from 18,000 to 19,000, total soil erosion increased by approximately 100,000 t and total harvested volume increased by 100,000 m^3 during the planning horizon.

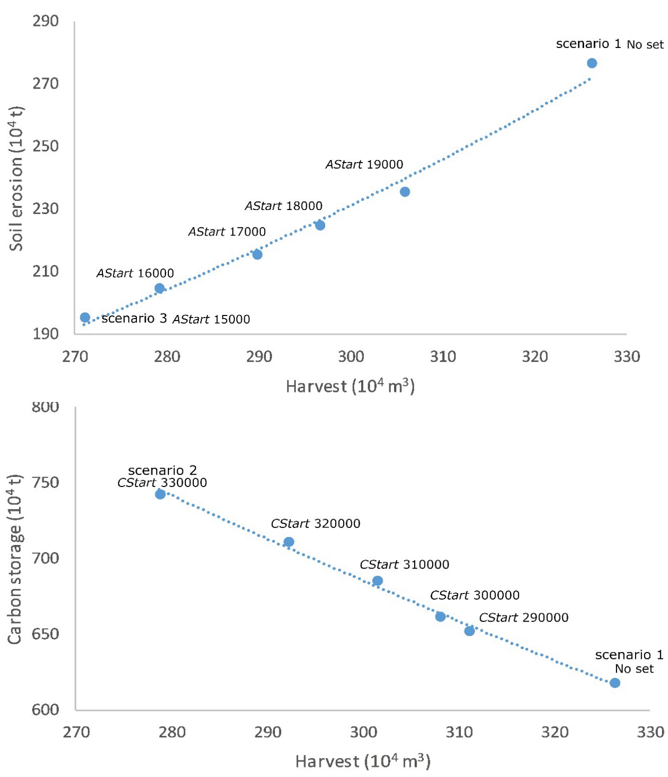

Figure 7. Trade-off curves between a) harvested volume and carbon storage, b) harvested volume and soil erosion. The total harvested volume is shown on the x-axis, whereas either total carbon storage or soil erosion is shown on the y-axis across 120 years (24 five-year periods). The points represent the results from various scenarios under different constraints.

As for the carbon balance, Equation 21 was used to calculate the carbon changes associated with each five-year season in a way that considered growth and clear-cutting during the planning horizon. Both carbon emissions and absorption are generally concentrated in stands representing site classes 3 and 4. In Scenario 1, carbon emissions exceeded carbon absorption in all the periods except for the 8th period (**Figures 8, 9** and **10**). In Scenario 2, carbon emissions exceeded carbon absorption in about two-thirds of the periods, while in Scenario 3 carbon emissions exceeded carbon absorption in about four-fifths of the seasons.

The age class distribution were illustrated in terms of site class across the 24 five-year planning periods for each of the three scenarios (**Figures 11, 12** and **13**). The distributions presented for each distinct scenario across the study period were smoothed relative to Figure 2, i.e., the initial unimodal age class distribution. In particular, Scenarios 2 and 3, when compared to Scenario 1,showed an increase in the number of Target FMU that were designated as no-cutting zones, which significantly increased the forest areas representing the age class of 120 years and above.

The implementation of the optimized harvest schedule appeared to change the forest conditions. For instance, soil erosion in the study area stayed rather

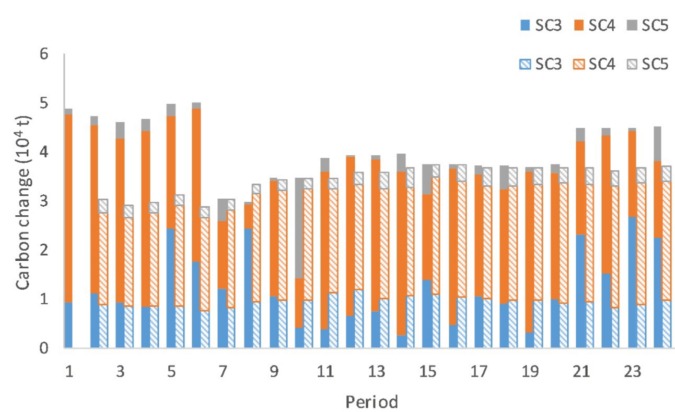

Figure 8. The change in the carbon pool for each of the 24 five-year periods (Scenario 1). The periods are shown on the x-axis, while changes in carbon storage are shown on the y-axis. The stronger colors (left) represent the carbon emissions, while the lighter colors (right) represent carbon absorption. Regarding the legend, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

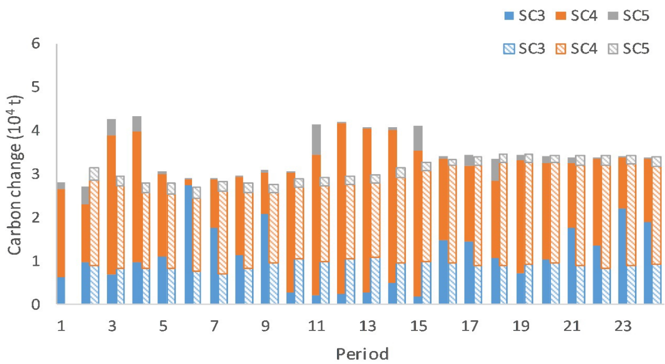

Figure 9. The change in the carbon pool for each of the 24 five-year periods (Scenario 2). The periods are shown on the x-axis, while changes in carbon storage are shown on the y-axis. The stronger colors (left) represent the carbon emissions, while the lighter colors (right) represent carbon absorption. Regarding the legend, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

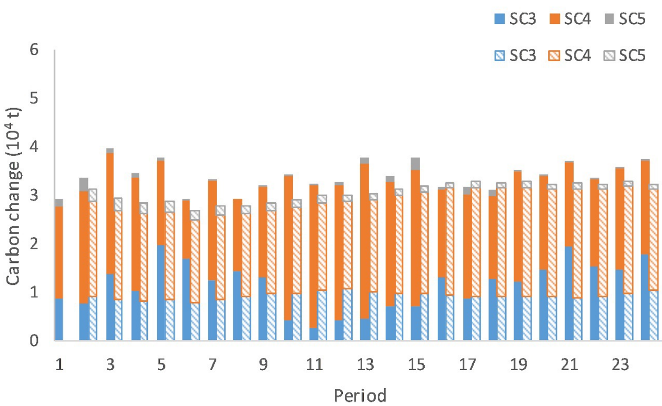

Figure 10. The change in the carbon pool for each of the 24 five-year periods (Scenario 3). The periods are shown on the x-axis, while changes in carbon storage are shown on the y-axis. The stronger colors (left) represent the carbon emissions, while the lighter colors (right) represent carbon absorption. Regarding the legend, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

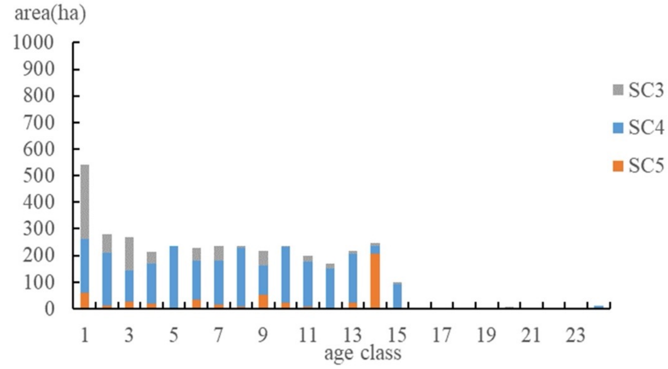

Figure 11. Age class distribution in the 24th period (years 115-120 of a 120-year time horizon) under scenario 1. After the simulated 120-year period (24 five-year periods), some age classes showed stable and similar prevalence in the study area. Regarding the legend, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

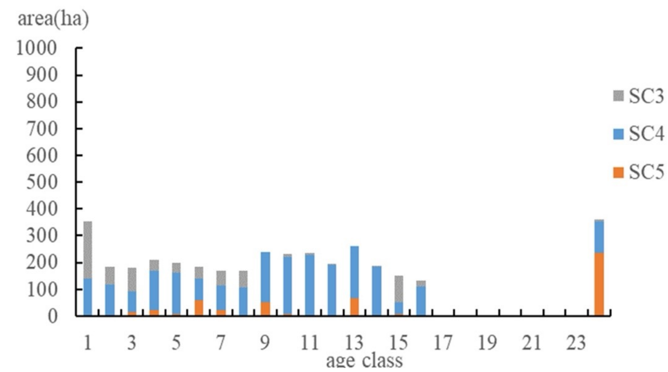

Figure 12. Age class distribution in the 24th period (years 115-120 of a 120-year time horizon) under scenario 2. After the simulated 120-year period (24 five-year periods), some age classes showed stable and similar prevalence in the study area. The 24th age class covers a large area because some of the Target FMU were assigned the no clear-cutting prescription. Regarding the legend, “SC3”, “SC4”, and “SC5” correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

constant, although there were dramatic changes in the spatial distribution of this public interest function within the target area. A comparison of scenarios 1 and 2, which includes a constraint on carbon storage, reveals differences in the spatial distribution of dark-colored Target FMU and suggests that certain Target FMU were assigned different prescriptions between scenarios 1 and 2 based on forest management priorities.

According to the legend, areas with a darker shade of color will experience more soil erosion.

In particular, it was possible to visualize the spatial distribution of soil erosion that increases with the area cut compared to the initial state (**Figure 14a**). Furthermore, it was possible to visualize that Scenario 2 (**Figure 14b**), which has a larger amount of cutting, occupies an area with a relatively larger amount of soil erosion compared to Scenario 3 (**Figure 14c**).

In this study, one sugi plantation in Japan was chosen as the target FMU, which spanned 3643 ha after the areas depicted in blue and green (**Figure 1b**) were excluded.

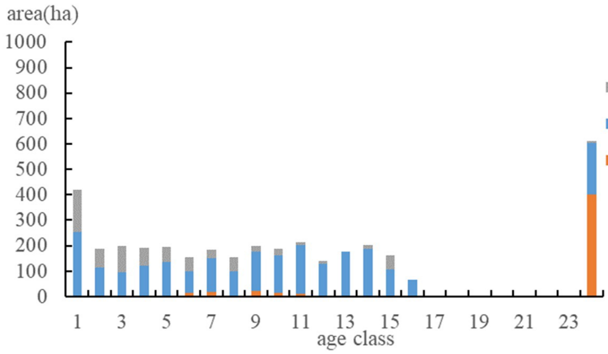

Figure 13. Age class distribution in the 24th period (years 115-120 of a 120-year time horizon) under scenario 3. After the simulated 120-year period (24 periods), some age classes showed stable and similar prevalence across the study area. The 24th age class covers a large area because some Target FMU were assigned the no clear-cutting prescription. Regarding the legend, "SC3", "SC4", and "SC5" correspond to areas classified as site class 3, site class 4, and site class 5, respectively.

The dynamics of various indicators were then modeled across 24 five-year periods. Adding constraints related to public interest functions to the harvest plan extended the cutting age and increased the number of forests that were assigned the no-felling prescription (**Figure 5**). An assessment of the changes in age class distribution between the three scenarios revealed that Scenario 1 demonstrated a shift from a unimodal to a uniform distribution, while the distributions observed for Scenarios 2 and 3 at the end of the 120-year study period were skewed towards the oldest age classes due to the growth of no-cutting prescriptions (**Figures 11-13**). An increase in the area of mature forest stands will also increase the area of forests containing large numbers of large-diameter trees. This can be expected to improve water resource conservation, which was one of the public interest functions included in Ccenarios 2 and 3.

Notably, Scenario 3 included a large proportion of areas representing site class 5 (trees aged 24 years and above), and a far smaller proportion of site class 3 areas. Forests that fall under site class 3 grow well and are mainly assigned for harvesting. This type of forest management decreases soil erosion and increases carbon storage because site class 3 areas are primarily subjected to harvesting while site class 5 areas (which are steep) are left intact, which promotes carbon storage and mitigates soil erosion. Since large areas of the study site represent site class 4, some of the Target FMU in these areas were destined for wood production, while other Target FMU were assigned public interest functions; the constraints included in the harvest schedule model influenced the ratio of these Target FMU. The harvest schedules that were optimized solely to maintain timber production

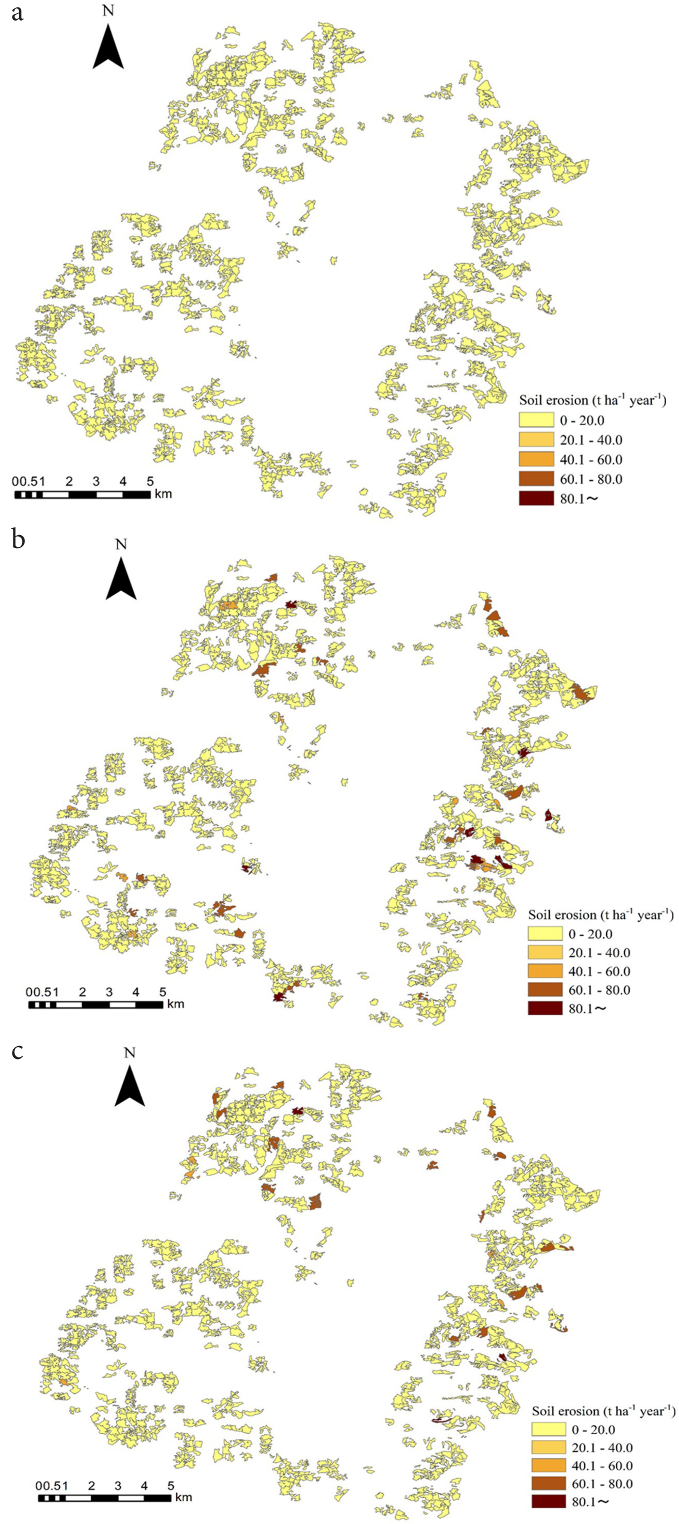

Figure 14. Soil erosion per hectare within the study area at the start of the study (a), soil erosion per ha at the end of the simulated 120-year period (24 five-year periods) under Scenario 1(b) and Scenario 2 (c).

translated to regeneration cutting in the Target FMU that showed high productivity, while low-productivity forests on steep slopes were set aside for public interest functions. This type of allocation is a way to comprehensively realize the multi-functional nature of forests.

The scenarios were similar in the sense that both carbon emissions and absorption were concentrated in site classes 3 and 4 (**Figures 8-10**). The main reason why carbon emissions are concentrated in site classes 3 and 4 is that these site classes are clear targets of logging operations. On the other hand, the large proportion of carbon absorption at site classes 3 and 4 is thought to be a result of the rapid growth of young trees planted after clear-cutting. The reason that Scenario 1 demonstrated higher carbon emissions than carbon absorption across 23 of 24 seasons is because under this scenario, timber production through logging was maximized without a set limit on carbon accumulation. In contrast, Scenarios 2 and 3, which involve a constraint related to a public interest function, showed a reduced area of logging operations relative to Scenario 1. This could explain the existence of fewer periods in which carbon emissions exceeded carbon absorption. It is important to note that carbon emissions exceeded carbon absorption across most of the five-year periods for all three scenarios.

The first step, comparing scenarios based on differences in site class distribution, provided some insights into the differences between scenarios, i.e., those with and those without public function constraints. Next, it was confirmed that the trade-offs (*Schwaiger et al. 2019*) between various forest functions for adaptive management can be quantified (*Hörlet al. 2020*). This is related to the results illustrated in the trade curves (**Figure 7**); for instance, it suggested that the influence of the trade-off may decrease when the carbon storage (*CStart*) constraint is 300,000 t or less (**Figure 7a**). This could be due to the value of *CStart* wherein below 300,000 t, the constraint does not have much of an influence on the selection of an optimal solution, as this would be a rather minimal carbon budget. Moreover, the influence of the trade-off may decrease when the soil erosion constraint is 19,000 t or more (**Figure 7b**). In contrast, the parameter ranges are considered to have a relatively large negative influence on the overall volume of harvested timber, i.e., the objective function (**Figure 7**). A trade-off curve can be effective at guiding decisions involving the prioritization of several conflicting goals (**Figure 7**). Unlike the research presented by *Schwaige et al.* (*2019*), this study is unique such that it simultaneously evaluates spatial public interest functions and harvest productivity using GIS, and then visualizes the dynamics at play in these optimization problems via trade-off curves (*Wu et al. 2021*).

The data sources, methodological choices, and assumptions linked to the applied formulae should always be considered when evaluating the results of forest-related functions and mixed integer programming. This is because each of these aspects can introduce error, which will directly affect the reliability and precision of the results. In this study, indices related to site-specific conditions were calculated based on 10 years of meteorological data. It is important to note that issues such as recovery of above-ground forest biomass and changes in tree species composition (*Hotta et al. 2021*) were not considered. Regarding the Target FMU designated as no clear-cutting zones, delays in thinning and the presence of taller trees can both increase the risk of denudation following natural disturbances, such as wind damage (*Nakajima et al. 2009*), which would potentially decrease the public interest functions. However, natural disturbances are serendipitous events that are impossible to forecast and could be expected to impart negative influences across the entire study site.

Previous evaluations of the multi-faceted functions of forests have selected specific indicators for planning purposes. For example, *Eggers et al.* (*2019*) choose net present value and growing stock, along with the proportions of old forest, sparse forest, and forest with arboreal lichen to evaluate forest values in terms of economic, ecological, social and reindeer husbandry aspects, respectively. In another study, *Binder* (*2012*) considered non-timber forest products, carbon storage issues, game species densities, and forest recreational activities in timber management plans, while *Yamaura et al.* (*2021*) evaluated 10 types of forest pleiotropic functions. A comprehensive assessment of the forest ecosystem would yield an immense array of functions, all of which (for instance, biodiversity, ecosystem diversity, ecological niches, along with species and genetic diversity) would be rather impossible to include into a forestry model. *Díaz-Yáñez et al.* (*2019*) previously calculated the Shannon index, i.e., the diversity of species in a location, according to the base diameter area of various tree species to assess forest biodiversity. This is an example of how it is difficult it is to evaluate all the functions of a forests in a single study; rather, it is important to select the indicators which are linked to the study objectives. In this study, indicators corresponding to four typical public interest functions were integrated into the evaluation. The subsequent optimizations also took into consideration indicators such as income, labor requirements, volume, and subsidies. The present study is considered a valid starting point for future investigations of how different modes of forest planning impact both society and the environment.

While *González-González et al.* (*2022*) only included sustainable regeneration cutting in their analyses, the profitability of various prescriptions, including no clear-cutting (prescription 16) was taken into consideration in this research. It is believed that this will be beneficial to the diverse stakeholders of sugi plantations, each of whom has different priorities and ways of thinking. The allocation of certain no clear-cutting zones will reduce the area of eroded land and enhance public interest functions; however, this will negatively impact the economic performance of plantation forests. The presented research shows that flexible forest planning options are viable and realistic, and that the assignment of no-cutting operations can help forestry associations in times of labor shortages (*Nakajima et al. 2011*).

Furthermore, it is important to highlight that even research using multi-criteria decision-making (MCDM) approaches has not linked GIS data and logging target areas, which was the case in this study. Although prior studies (*Nguyen et al. 2024, Gebre et al. 2021, Ali et al. 2020, Çaliskan et al. 2019, Semmens et al. 2017*) have analyzed planting area, road network design, and sustainability of forestry using MCDM, there is no example– to the best of current knowledge – that links GIS data describing the logging target area to the optimization approach. The presented research employed MIP, rather than the more popular MCDM, to obtain optimized, sustainable harvest plans for a sugi plantation in Japan. This methodology directlycompares the forest ecosystem services associated with different scenarios without arbitrary weighting. If MIP was used in conjunction with MCDM, it may be possible to automatically extract a scenario from a large number of candidates to build a realistic decision-making support system that combines automated and non-automated decision-making. This is related to another challenge of this type of research. For instance, *Hernandez et al.* (*2014*) normalized indicators related to many objectives and aggregated them into one objective function, after which certain constraints related to carbon storage and soil erosion were added. It should be noted that although normalizing metrics enables comparison and the optimization of all the metrics through a single objective function, these normalized metrics nevertheless do not represent reality. The purpose of this study was to evaluate the multi-faceted forest functions that influence the objective of maximizing harvested timber. Thus, harvested timber (an economic indicator) was compared with soil erosion and carbon storage (forest ecosystem indicators) to clarify the trade-offs between timber production and public interest function across three distinct scenarios. Therefore, the scheduling problem was optimized using mixed integer programming in a way that one index serves as the input for the objective function and the other indices are used as constraints.

The harvesting method adopted in this study corresponds to timber production by regeneration-cutting and thinning. This mode of silvicultural management was chosen because it is relevant to the nuances of Japanese forest management. The computing power of modern computers was leveraged to provide strategic plans on how to manage a sugi plantation in a way that would be Japan. This methodology directly compares the forest ecosystem services associated with different scenarios without arbitrary weighting.

In relation to the consolidation of forestry operations, *Hernandez et al.* (*2014*) included spatial restrictions in the harvesting area, and then optimized forestry operations. The present study also considered the issue of maximum harvesting area by including a constraint for the size of stand that could be harvested. The method of consolidating adjacent forest stands to form Target FMU is a suitable method in Japan, where many forest owners are small-scale foresters who manage an area of about 1 ha. In this study, the FMU area was set to 3 ha or more because this represents a stand size that can be efficiently harvested; similar efficiencies cannot be realized in smaller areas.

In Japanese forestry, the government formulates detailed plans in a top-down manner; these plans are then distributed to the national, prefectural, and municipal governments. Municipal governments are then expected to formulate plans in a bottom-up manner through conversation with forestry associations. The following paragraph will discuss how the research can benefit the way in which Japanese forests are managed. Concerning the top-down generation of plans, the presented model can automatically select and combine the harvest schedules for each FMU; in this way, the forest management plan and harvest schedule will be linked.

The presented model is relevant for timber production functions, and, more specifically, how the most profitable schemes are desirable for forest owners in contemporary society. In other words, foresters aim to maximize the profits of plantation forests. Among the three scenarios proposed in this study, Scenario 1 was associated with the greatest economic benefits because there were neither constraints on soil erosion nor carbon storage. This scenario was associated with large, harvested volumes, yet profits were not maximized. This suggests that various factors related to the economic performance of a planted forest (e.g., costs linked to labor requirements and machinery, along with total harvested volume) should be considered when planning the harvesting schedule.

The presented research is also relevant in terms of the growing demand for sustainable forest management, as two of the analyzed scenarios included public interest functions, more specifically, soil conservation and carbon storage. Based on the concerns of citizens, government institutions aim to promote sustainable forest management, with the prioritization of the public interest functions of forests one viable approach for achieving this.

In this study, the various indicators were evaluated for both the entire study area as well as for each FMU (**Figure 14**). As such, both economic performance (a priority for forest owners) and public interest functions (a priority for the general public) were simultaneously quantified. This means that ratios of the two priorities can be calculated, which can contribute to both the drafting of top-down and bottom-up plans for sustainable forest management.

Forests improve the local environment and citizens' quality of life through multi-faceted functions. Since the fiscal year of 2019, the Japanese government has been issuing a forest environment transfer tax to prefectural and municipal governments. The governments are tasked with allocating this sum to thinning operations, improving human resources, securing forest workers, and promoting the use of wood. The Japanese government also draws upon regional zoning to investigate the utilization status of forest resources, the extent to which forest maintenance has been implemented, and potential projects that will improve the public interest functions of forests. In the case of Yamagata prefecture, this zoning only considers harvested areas using a 50-m mesh topographic map. Moreover, the forest environment transfer tax is divided based only on timber production. In this study, harvested volume, soil erosion, and carbon storage were calculated at the FMU-level; this level of resolution (FMU-level) could prove useful in the efficient dissemination of the forest environment transfer tax.

The model presented in the study had clear trade-offs, and subsequent analyses enabled the quantification of the extent to which regional timber production would decline when certain public interest functions were taken into consideration. As timber production is an indicator of economic performance, the methodology presented in this study can be used to quantify the economic opportunity cost for various forest management strategies based on trade-offs between economic and environmental functions. The results of this study provide evidence of opportunity costs, and a rational subsidy system could help offset the economic opportunity costs when forest owners balance environmental and economic forestry functions.

Mazziotta et al. (*2023*) identified the presence of dead trees as an environmental indicator of increasing biodiversity. The same research group compared this indicator with net present value to analyze the trade-offs between economic and public forest functions. The present study differs from the previous study (*Mazziotta et al. 2023*) in that the methodology enables decision-makers to evaluate the opportunity cost associated with the promotion of two environmental functions, namely, carbon storage and/or soil conservation.

It is well-established that trade-offs between two functions can be expressed in two-dimensional space, but trade-offs between three or more functions would be more complex to illustrate. In the present study, it was illustrated how three scenarios, which differed in the prioritization of economic and public interest functions, changed the age structure and other characteristics of a forest area over a 120-year horizon.

CONCLUSIONS AND RECOMMENDATIONS

In this study, a methodology was presented which to help forest owners quantitatively analyze the multi-faceted functions of forests and formulate long-term harvesting schedules that consider certain important public interest functions. As there is a growing concern about the negative effects of forestry, this will provide forest managers with harvesting plans that still meet their expectations of forest production. As the consideration of public interest functions will undoubtedly decrease timber production, and result in decreased economic profits, it will be essential for decision-makers, at both the local and national levels, to contemplate mechanisms that can be used to offset these losses.

Both the economic interests tied to a harvest schedule, which are a primary concern for forest owners, and the public interests related to a forest management plan, which are relevant for the government during shifts about nature conservation, were quantified. This approach enabled the comparison of changes in the harvested volumes when different interests were prioritized, or in other words, balancing forest management plan and harvest schedule dynamics over a spatial scale.

Various sustainable strategies and plans were also analyzed by considering the trade-off curves between timber harvesting and public interest functions, more specifically, carbon stock and soil erosion. This allowed a comprehensive picture to be painted of how the government, forest owners and other stakeholders can balance timber production with public interest functions that will noticeably decrease economic performance under the objective of achieving long-term environmental sustainability.

The next challenge will be analyzing various sustainable strategies and plans by considering the trade-offs between four or more forest functions. This could yield insight into how the government can better offer subsidies to offset for decreased economic performance under mandated plans of long-term sustainability. If MIP is used in conjunction with MCDM, it may be possible to automatically extract a certain scenario from a large number of scenario candidates to build a realistic decision-making support system that combines automated and non-automated decision-making. This was a clear limitation of this study and a topic that should be formalized in the future.

In this study, the focus was placed solely on artificial Japanese cedar forests, which are mainly affected by human activities and can be harvested in a way that is economically viable. In addition, a specific study area was selected because the site contained only one main tree species (Japanese cedar), with most of the trees being the same age; this enabled a focus solely on target FMU forests which are subjected to human activities. For these reasons, it was acceptable to only target the selected Target FMU because the purpose of the research was to evaluate anthropogenic activities. The next challenge will be evaluating public benefit functions across a larger area, i.e., one that includes both natural and artificial forests.

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