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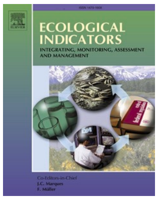

Spatially explicit optimization of the forest management tradeoff between timber production and carbon sequestration

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ABSTRACT

Forest farms are the main body of forest management at the landscape-scale in China, and have long sought ways to jointly maximize timber production and other ecosystem services. Carbon sequestration is of particular interest because China has established the goal of becoming carbon neutral by 2060. However, optimizing the balance between timber production and carbon sequestration is a challenge due to a lack of methods that account for the spatial arrangement of forest management activities within a landscape. This study developed a multi-objective planning model for forest management approaches to promote natural forest regeneration, adjusting the stand age structure of plantation forests to an even distribution across a landscape, and quantified the effects of social preferences and market prices on optimal management. The results show that depending on the dominant ecosystem services provided by the forests, forest management could promote an increased timber volume and stand carbon stock that is sustainable in the long-term. Social preferences have a relatively small influence on optimal management plans after forests are restructured to a normal forest age class distribution. In addition, forest management dynamics are more sensitive to carbon prices than timber prices. Hence, the spatial allocation of different management practices and forest restructuring, rather than protecting forests or managing them less intensively, is more effective for improving forest carbon stocks. More importantly, an urgent need also exists to increase the carbon price to guide and strengthen the attention of forest managers to forest carbon sequestration, with the goal of achieving a win–win strategy.

1. Introduction

Forests provide numerous goods and services that are important for human society, including timber production and carbon sequestration. Timber production is a provisioning service that supplies humans with high-demand renewable raw materials and is often the main source of income for forest managers (Gerasimov et al., 2012; Ouyang et al., 2021). Global climate change, which is caused by the anthropogenic increase in atmospheric carbon dioxide, leads to drought and land degradation and greatly affects plants, food security and agricultural practices (Fahad et al., 2019, 2021a,b,c). Carbon sequestration is crucial to climate change mitigation and can be fostered through both afforestation and forest management (Kolström et al., 2011; Nunes et al., 2020). As demands on forests have become more diverse, forest management has generally shifted from traditional timber production-oriented management to multipurpose management that is often based on ecosystem services (Liu et al., 2015). In order to reduce carbon emissions and combat climate change, effective forest management should consider the tradeoff between timber production and carbon sequestration (Bradford and D'Amato, 2012; Pohjanmies et al., 2017).

Forest management activities usually involve a series of silvicultural practices, such as planting, seedling tending, thinning, selective cutting, and clear-cutting. These activities are important for maintaining sustainable timber production and carbon sinks in plantations (Kang et al., 2016; Kucuker, 2019; Schwaiger et al., 2019). The decision alternatives associated with tactical forest planning include considering all possible combinations of management strategies for the basic management units. This produces the enormous decision space of the forest planning

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problem (Kaya et al., 2016). Thus, the current problem formulations of the traditional methods such as linear and goal programming are not sufficient for today's forest planning problems, which are often multi-objective, involve multiple parties, and are non-linear and spatial (Baskent and Keleş, 2009; Borges et al., 2002). Some studies have used process-based models such as 4C, SIMA, and InVEST to simulate different forest management strategies (Alrahahleh et al., 2017; Augustynczik et al., 2020; Bottalico et al., 2016). Nevertheless, these models require location-specific input data to calibrate the parameters when they are applied to new regions. In recent years, various heuristics have been used in forest management planning due to their advantages in solving large mathematical planning problems (Liu et al., 2006; Pukkala and Heinonen, 2006). Among these algorithms, simulated annealing has attracted extensive research attention because it has advantages in terms of computational time and independence (Borges et al., 2014; Moriguchi et al., 2017). Some studies applied a simulated annealing algorithm to develop a forest planning model incorporating timber production and carbon sequestration objectives (Dong et al., 2015; Liu et al., 2017). Although the simulated annealing algorithm provides an effective tool, new algorithmic programs are required for the method to solve the complex forest planning problems, which involve the configuration of management measures for specific spatial units at the landscape scale and consider socio-economic factors.

In China, forest farms serve as the administration bodies for forest-land management, these farms formulate and implement specific management plans. The management of a forest farm should simultaneously consider economic aspects, the environment and social responsibility (Qiao, 2018). However, long-term extensive forest management with economic benefits from timber harvest as a primary goal has often resulted in unreasonable stand structures and declining forest quality. In China, since forest farm reform started in 2015, the new focus has been on arranging silvicultural measures based on the theory of classified management, that is, different forest categories should adopt different logging methods to achieve multipurpose management (Li et al., 2016). In addition, the age class structure of forests at the landscape level is closely related to both timber production and carbon sequestration dynamics (Ouyang et al., 2019; Song and Woodcock, 2003; Zeng et al., 2021). A reasonable age structure can ensure the sustainable production of timber. Maximum production occurs during early growth stages in a forest, while the rate of carbon sequestration decreases with stand age and net ecosystem production approaches zero as a forest matures (Ryan et al., 1997). However, the results reported by Luyssaert et al. (2008) illustrate that old trees continue to store carbon at a steady rate. Consequently, the forest optimization process must consider how management activities can be rationalized in time and space; it should focus on restructuring the age structure of the forest to best meet the objectives of the forest manager.

In addition, forest managers need to consider the influence of social preferences and market prices of forest products. Different stakeholder groups envision different levels of importance on the roles they envision forests should have in; for example, the national economy, the sustainable provisioning of ecosystem services, and climate change mitigation (Sandström et al., 2020). Thus, different people have varied perceptions of the most important priorities in forest management. The optimization process can incorporate preferences by means of weighting or penalties and provide timely feedback that can be of great value to operational decisions required during forest management (Knoke et al., 2020). Meanwhile, the prices of various forest products and types of management activities represent a complex system from an economic perspective, affecting different flows of goods and services. Previous studies indicated that when either timber or carbon prices increase, managers will extend rotations to obtain more revenue, thereby increasing timber harvest volumes or forest carbon stocks (Chen et al., 2017; Liski et al., 2001). However, few studies have explored the sensitivity of forest management to timber or carbon prices.

Overall, the lack of a more intelligent algorithmic program, neglecting age structure adjustment, and insufficient knowledge about how perception of the social-economic system influences forest management have become major barriers for multi-objective forest management. Against this background, the present study attempts to use a representative forest farm in southwestern China as a case study to propose an integrated approach designed to rationalize forest management activities (clear cutting or selective cutting) and assess the effects of social preferences and market prices on long-term forest management dynamics. To this end, the specific objectives are to (1) develop a spatially explicit forest planning model that takes into account classification management theory and the adjustment of plantation age structure that is designed to simultaneously improve timber production and carbon sequestration; (2) examine whether social preferences affect the total benefit of timber production and stand volume and carbon stocks of a forest farm; and (3) analyze the sensitivity of forest management and stand volume and carbon stocks to timber and carbon prices.

2. Materials and methods

2.1. Study site description

This study was carried out in the Paiyashan Forest Farm (26°24′to 26°35′N and 109°27′to 109°38′E), located in the southwestern Jinzhou County, Hunan Province, China (Fig. S1). This area is characterized by mountainous landscapes with elevation ranging from 400 m to 800 m and an average slope of 25°. The mean annual temperature in the study area is 16.7 °C and the mean annual precipitation is 1250 mm. The mainly red fertile soil is of good quality.

The Paiyashan Forest Farm covers an area of 6486 ha, of which 43.64 % is natural forests, 39.85 % is plantation forests, and the remaining are is non-forest land. The natural forests in the study area include mixed broad-leaved deciduous and broad-leaved evergreen forests (789.5 ha) along with Masson pine (*Pinus massoniana*) forests (2032.3 ha). The plantation forests include Chinese fir (*Cunninghamia lanceolata*) forests (1924.9 ha) and Masson pine forests (660.2 ha). Table 1 shows the forest resource status of the study area. According to the age group and age classification standards of the main tree species (State Forestry Administration, 2017), Chinese fir and Masson pine plantations were divided into different age classes using 5- and 10-year intervals, respectively. Each age group contains one or two age classes, depending on forest origin and tree species. The detailed age classes and age groups of all forests are presented in Table 1. Overall, few over-mature forests exist in the study area. The age distribution of the plantation forests is very heterogeneous, with a lack of mature and over-mature stands of Chinese fir and a lack of young stands of Masson pine plantations.

2.2. Optimization framework

Fig. 1 shows the optimization framework. Our forest alternatives are designed to be implemented at the basic forest management unit level, using forest inventory data as input data for the assessment of ecosystem services. The optimal harvesting schemes satisfying the constraints under the management objectives are obtained by simulated annealing, with attention to changes in forest structure and the dynamics of ecosystem service provisioning. The planning duration in this study was 100 years (2020–2120); this was divided into 20 intervals of 5 years each to optimize forest management.

2.2.1. Data

We based the forest inventory map on 1712 basic management units ranging from 0.5 to 40 ha, with an average size of 3.6 ha ($SD = \pm 3.9$) consistent with the basic management units implemented in local forest management practices. We obtained the average slope, dominant species, average age, stand volume and stand carbon stock for each basic management unit from the forest inventory data. With these data we

Table 1
Forest resources status in Paiyashan forest farm in 2019.

Forest origin	Forest type	Age group	Age class	Age	Area (ha)	Forest volume (m^3)
Natural forests	Masson pine	Young	I	0–10	13.00	0
			II	11–20	617.66	184.85
		Middle-aged	III	21–30	15.37	1721.68
		Near-mature	IV	31–40	71.92	2567.98
		Mature	V	41–50	1314.30	125297.29
			VI	51–60	0	0
		Over-mature	≥VII	≥61	0	0
	Deciduous and evergreen broadleaf tree species	Young	I	0–20	30.23	161.57
			II	21–40	43.82	2606.14
		Middle-aged	III	41–60	183.25	15688.20
		Near-mature	IV	61–80	98.20	6985.16
		Mature	V	81–100	442.95	41713.89
			VI	101–120	0	0
		Over-mature	≥VII	≥121	0	0
Plantation forests	Chinese fir	Young	I	0–5	395.58	0
			II	6–10	34.89	1174.58
		Middle-aged	III	11–15	26.70	2661.34
			IV	16–20	264.38	18856.00
		Near-mature	V	21–25	1203.30	199595.53
		Mature	VI	26–30	0	0
			VII	31–35	0	0
		Over-mature	≥VIII	≥36	0	0
	Masson pine	Young	I	0–10	0	0
		Middle-aged	II	11–20	117.63	70.97
		Near-mature	III	21–30	0.44	16.54
		Mature	IV	31–40	37.40	2042.22
			V	41–50	503.84	53605.14
		Over-mature	≥VI	≥51	0.92	35.14

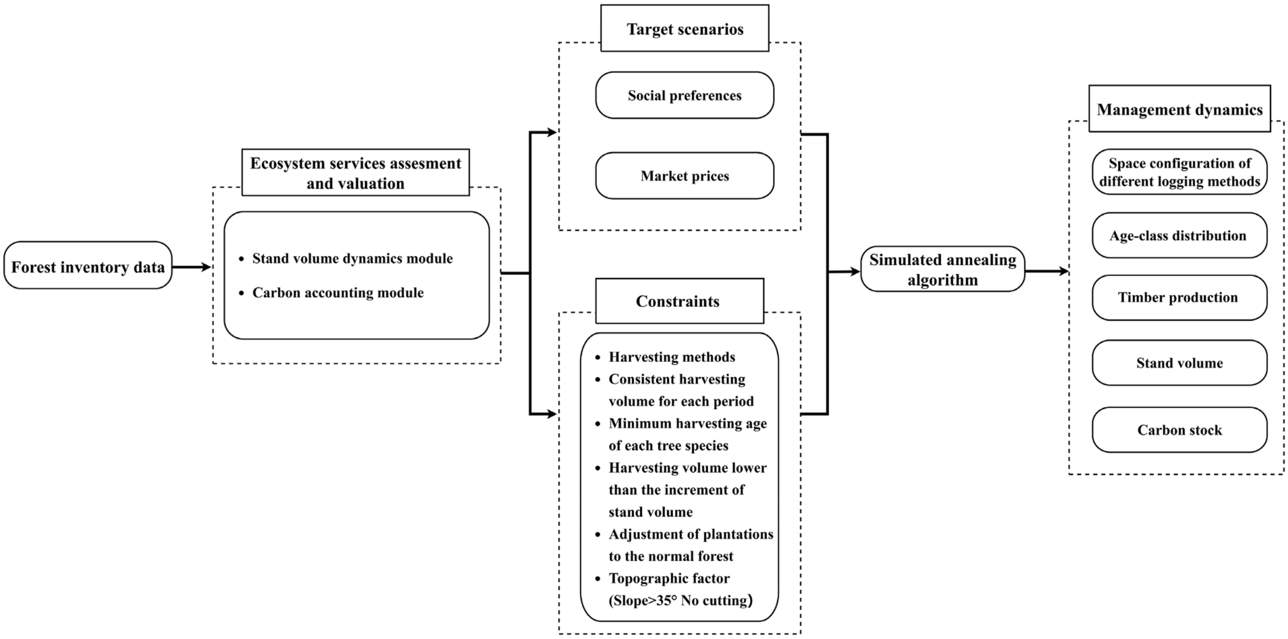

Fig. 1. Optimization framework based on the simulated annealing algorithm.

carried out the following optimization process.

2.2.2. *Ecosystem service assessment and valuation*

2.2.2.1. Timber production. Timber yields were estimated using stand growth models and empirical yield tables for Chinese fir prepared by Xiang et al. (2022) and for Masson pine prepared by Cheng et al. (2003). Broad-leaved forest stand volume was estimated using the biomass expansion factor method of Fang et al. (2014). Volumes of various timber products as a result of clear-cutting and selective cutting at any age were determined based on the available merchantable volume ratio tables. We converted all revenues and costs to net present value (NPV) using the discount rate of 3 % per annum which has commonly been used for forestry projects (Kim et al., 2015; Lee et al., 2020; Markandya, 2019). Our costs included timber production costs, timber sales taxes and silvicultural costs (State Forestry Administration, 2016). The related calculations of timber production can be expressed as:

$$HV_{t,k} = Area_k \times V_{k,t} \times X_{k,t} \times LT_j \forall t,k \tag{1}$$

$$NPV^{timber} = \sum_{t=1}^{T}\sum_{k=1}^{N}\frac{HV_{t,k}\times\left(MP_{t,k}-TC_{t,k}\right)}{(1+p)^{t\times PL}} \tag{2}$$

where $Area_k$ is the area of unit k; $V_{k,t}$ is the volume per hectare of unit k in period t; $X_{k,t}$ is a binary variable indicating whether unit k is harvested or not in a specific period t; LT_j represents the logging intensity of logging type j (clear-cutting or selective cutting); $HV_{t,k}$ is the harvest volume unit k in period t; $MP_{t,k}$ is the market price for the timber of unit k in period t; $TC_{t,k}$ is the total cost for the timber of unit k in period t; N is the number of management units; T is the total numbers of periods (20) for the 100-year time frame; p is the discount rate in percentage; NPV^{timber} is the total discounted NPV of timber during the entire planning horizon; and PL is the length of each 5-years period.

2.2.2.2. Carbon sequestration. Considering there is fewer available spatial data related to wood-based products, dead wood and soils, forest carbon stocks in this study were mainly composed of the aboveground and underground biomass carbon of living trees. We calculated the biomass for each forest type using biomass estimation equations from Cheng et al. (2003), Wang et al. (2018), and Xiang et al. (2022). Tree biomass was multiplied by 0.5 to convert into biomass carbon storage (Xu et al., 2010). When calculating the NPV of carbon sequestration, the net sequestration for successive periods was estimated as the difference between the total remaining carbon in one period and in the previous period (Boyland, 2006) and then multiplied by the constant 3.67 (conversion coefficient for converting carbon storage to CO_2 equivalent) (IPCC, 2006). The formula for carbon sequestration can be expressed as follows:

$$C_{residual,t} = \sum_{k=1}^{N}\left(C_{above,k,t}+C_{under,k,t}\right) \tag{3}$$

$$\Delta C_t = C_{residual,t} - C_{residual,t-1} \tag{4}$$

$$NPV^{carbon} = \sum_{t=1}^{T}\frac{\Delta C_t \times P_c}{(1+p)^{t\times PL}} \tag{5}$$

where $C_{above,k,t}$ is the residual aboveground carbon stocks of unit k in period t; $C_{under,k,t}$ is the residual underground carbon stocks of unit k in period t; $C_{residual,t}$ represents the total remaining carbon stocks in time period t; ΔC_t denotes the net carbon sequestration from time period $t-1$ to time period t; P_c is the price of carbon stock per ton; NPV^{carbon} is the total discounted NPV of net carbon sequestration; and the discount rate p (3 %) is used over the entire planning horizon.

2.2.3. *Target scenarios and constraints*

The detailed description of each scenario is shown in Table S1. In order to examine the effects of social preferences on the total benefit of timber production, stand volume and carbon stocks, we set five social preference scenarios, namely T100C0, T75C25, T50C50, T25C75, and T0C100, by assigning weights (T values) of 100 %, 75 %, 50 %, 25 %, and 0 % to the NPV^{timber} variable and corresponding weights (C values) of 0 %, 25 %, 50 %, 75 %, and 100 % to the NPV^{carbon} variable as the optimization objectives of the model. Because most forests in China are still young, the government has adopted the felling ban policy that is in place on the most important farms. Hence, we established a no management scenario, which was in line with the felling ban as the reference scenario.

Timber and carbon prices also affect silvicultural activities and are important instruments in mitigating greenhouse gas emissions. In order to analyze the sensitivity of forest management, stand volume, and carbon stocks to timber prices and carbon prices, we set the NPV^{timber} and the NPV^{carbon} as equal weights in the objective function and then optimized the forest management for different price levels of carbon and timber. In this case, P_T1, P_T2, and P_T3 were the low, mid-range, and high price levels, respectively, for timber products of three species (Chinese fir, Masson pine, and broad-leaved trees) which were retrieved from the China Timber Organization (2021) as shown in Table S2. In addition, P_C1, P_C2 and P_C3 were the low, mid-range, and high prices of the carbon trading market, respectively, shown in Table S2. In this study, P_C1 was 50 RMB per ton of carbon corresponding to the average market price for carbon trading in China (China Carbon Emissions Trading, 2021). Meanwhile, P_C2 represented the mid-range price (1000 RMB per ton of carbon) derived from The World Bank (2021), and P_C3 (2000 RMB per ton of carbon) was the relatively high carbon price mentioned in Austin et al. (2020). Nine scenarios with different combinations of timber prices and carbon prices were developed to analyze the sensitivity of forest management, stand volume, and carbon stocks to timber and carbon prices.

We set the following constraints in the model, including minimum harvesting age, harvesting volume lower than the increment of stand volume, relatively consistent harvesting volume for each period, and no harvesting activities in areas with slopes greater than 35°. Meanwhile, given that different forests can provide different dominant ecosystem services (Zeng et al., 2019), the corresponding harvesting method was also defined as a constraining condition. Natural forests are generally emphasized on their regulating services to maintain biodiversity and mitigate and adapt to climate change by preserving higher carbon stocks. Therefore, we adopted a selective logging method for natural forests with a logging intensity of 10 % of the basic management unit area per year to promote natural forest regeneration. Clear-cutting was used for plantation forests that are mainly focused on timber production. The effects of unexpected events such as wildfires or illegal harvest were not considered. In the planning model, we set the management units where clear-cutting has been carried out to be reforested within 1 year after harvest. Another constraint was to adjust the age structure of plantation forests.

Most forests in the Paiyashan Forest Farm are young, and this situation is common in subtropical China. Therefore, the first objective in this study is to adjust the age structure of plantation forests to the normal forest by using our forest planning model. Based on the tree growth rates in this study area, age structure of the plantations could be adjusted to the normal forest within the first 50 years of the planning period (2020–2070). The normal forest means that the forest land area of each age class ranging from zero (recently clearcut) to the desired rotation age is equal (Bettinger et al., 2017). In this study, the desired rotation age is the minimum harvesting age, determined by the maturity age of a specific tree species, i.e., 30 years (age class Ⅵ) for Chinese fir plantations and 35 years (age class Ⅳ) for Masson pine plantations (Table 1). Therefore, we adjusted the age structure to normal forests with equal area of each age class, ranging from age class I to age class VI for Chinese fir plantations and from age class I to age class IV for Masson pine plantations during 2020–2070. The allowable error of the forest stand area of each target age class did not exceed 20 %.

The management objective is defined as follows:

$$Maximize Z = weight \times NPV^{timber} + (1-weight)\times NPV^{carbon} \tag{6}$$

subject to:

$$HV_t = \sum\nolimits_{k}^{N} HV_{t,k} \tag{7}$$

$$0.8 \le \frac{HV_t}{HV_{t+1}} \le 1.2 t = 1,2,\cdots,T-1 \tag{8}$$

$$HV_t \le GV_t t = 1,2,\cdots,T \tag{9}$$

$$X_{k,t} = \begin{cases} \{0\} Age_{k,t} \le Age_s^{min} or slope_k \ge 35^{\circ} \\ \{0,1\} Age_{k,t} \ge Age_s^{min} and slope_k < 35^{\circ} \end{cases} \tag{10}$$

$$a_{s,r} = \sum\nolimits_{k}^{m_{s,r}} Area_k r \in DNF_s \tag{11}$$

$$0.8 \times \frac{\sum_{k}^{M_s} Area_k}{NC_s} \leq a_{s,r} \leq 1.2 \times \frac{\sum_{k}^{M_s} Area_k}{NC_s} \tag{12}$$

where HV_t is the total volume of all timber products in period t; GV_t is the growth volume in period t; $Age_{k,t}$ is the stand age of management unit k when it was managed in period t; Age_s^{min} is the minimum harvest age assumed for forest type s, in which s is a variable that represents one of the three forest types; $slope_k$ is the slope of management unit k, which is calculated and recorded by geographic information system (GIS); $a_{s,r}$ is the area of the r age class of the forest type s; $m_{s,r}$ is the number of all management units of forest type s with age class r in 2070; and DNF_s is the set of target age classes for forest type s. M_s is the number of all management units of forest type s; NC_s is the number of target age classes for forest type s.

In this model, Eq. (6) maximizes the discounted $\mathrm{NPV}^{\mathrm{timber}}$ and $\mathrm{NPV}^{\mathrm{carbon}}$ during the entire planning horizon. Eqs. (7)–(8) concern the even timber flow constraint (i.e., the timber amount HV_t harvested at each key time must be no less than 80 % and no higher than 120 % of HV_{t+1} harvested during its next time period). Meanwhile, Eq. (9) means that the harvesting volume at period t would not be allowed to exceed the growth volume in period t. In addition, Eq. (10) means that the same management unit is not allowed to be arranged for multiple logging operations at the same time, and logging is allowed only when the requirements of the minimum logging age and flat terrain are met at the same time. Eqs. (11)–(12) indicates that the area of each target age class of forest type s in 2070 should be within 80 % and 120 % of the required age class area for that forest type.

2.2.4. Access optimized solutions

Simulated annealing is a type of Monte Carlo method that uses an intelligent search to find the best local combination of management interventions under various constraints for achieving management objectives (Bettinger et al., 2002). The most important parameters used in simulated annealing applications are an initial temperature, the number of iterations allowed at each temperature, the cooling rate, and the final temperature at which the search is finished (Bettinger and Kim, 2008; Tsallis and Stariolo, 1996). These parameters are related to the probability of finding the global optimum and the search time. In practice, the initial solution of simulated annealing can be generated randomly or obtained by the previous algorithm process. Then a random move would modify the current schedule one aspect at a time. Moves that improve the quality of the forest plan based on NPV are always accepted. Moves that fail to improve the quality of the forest plan are accepted based on a probability:

$$probability = e^{\frac{Z_{new} - Z_{old}}{T}} \tag{13}$$

where T is the current temperature of the annealing process; Z_{new} is the objective function value of the proposed solution; and $\mathrm{Z}_{\mathrm{old}}$ is the objective function value of the current solution.

Each move can use domain knowledge to guide the search according to the constraints, which can reduce the search space, enhance the local optimization ability, and improve the convergence speed of simulated annealing. Based on a series of quantitative simulations, the appropriate parameter values for planning problems are 1,000,00 degrees for the initial temperature, 10 degrees for the final temperature, 0.995 for the cooling rate, and 300 iterations at each respective temperature. This process resulted in approximately 551,100 iterations of each scenario being run independently. We executed multiple simulated annealing processes for each planning scenario, and then compared and obtained the best solution for each scenario to perform a follow-up analysis in this paper. Our forest planning model with the simulated annealing as the core was coded in the Python 3.8.8 programming language, and linked with GIS where the geographical data were processed and visualized using the "*geopandas*" package.

3. Results

3.1. Logging configuration and age structure adjustment

Our model could yield spatially explicit harvesting locations over the whole planning time (100 years) for forest manager. We presented an example of these results in Fig. S2 under the scenarios considering social preferences. Due to the unreasonable age structure of the forests during the early stages of this analysis, only a few resources available were for harvesting, and the proportion of areas subject to harvesting activities during the early stages of all scenarios was relatively limited. However, the proportion of areas subject to harvesting activities at the late stages increased and gradually stabilized after optimal management had been implemented. The proportion of different management measures varied among the scenarios. As the weighting of timber production increased, the proportion of areas with harvesting activities increased, and the ratio of selective to clear cutting increased. The scenario T100C0 had the most areas where selective cutting was carried out, accounting for about 21 % of the total area, and about 8 % of the area was subjected to clear-cutting in each planning period. In T0C100, the scenario with the highest carbon sequestration weight, the ratio of selective cutting to clear-cutting was the lowest, with an average of 6 % of the areas subject to selective cutting and 5.2 % of the areas subject to clear-cutting activities in each period. This indicated that T0C100 maximized carbon sequestration by reducing harvesting to protect existing forests as much as possible.

All optimization scenarios have adjusted the age structure of the plantations to a normal forest age distribution with approximately equal forest land area for each age class ranging from age class I to the desired age class during 2020–2070. Hereafter, the area of each age class is close to a normal forest age distribution during 2070–2120 (Figs. S3 and S4). Because no Chinese fir plantation resources were found that met the minimum harvesting age of 30 years (age class Ⅵ) initially, harvesting activities in Chinese fir plantation forests only started in the period 2025–2030. After 2060, the age structure (from age class I to age class VI) of the Chinese fir plantations remained relatively stable. In addition, the proportion of over-mature stands (≥age class VIII) retained increased as the $\mathrm{NPV}^{\mathrm{carbon}}$ weight in the target scenario increased. As for the Masson pine plantations, the plantation forests in the optimized scenarios initially had harvestable resources, so that the objective of adjusting the age structure to that of a normal forest age distribution (from age class I to age class Ⅳ) was achieved around 2055. The age structure of the plantation forests of Masson pine remained relatively constant during the period 2055–2120. In 2070, the allowable error in stand area for each target age class in both the Chinese fir and Masson pine plantations did not exceed 20 %, and all satisfied the normal forest age structure distribution constraint. In contrast, all the Chinese fir plantations and Masson pine plantations under the no management scenario grew into over-mature forests from 2055 onward.

3.2. Effects of social preferences on optimal management strategy

The five social preference scenarios with additional constraints of natural forest regeneration and adjustment of the age structure of plantation forests resulted in lower stand volumes and carbon stocks in the short term than the reference scenario (no management) due to having a higher timber harvesting intensity (Fig. 2). However, from the 30th year (6th period), the existing stand volume and carbon stock of all optimal scenarios were better than no management, especially T0C100, where the existing stand volume was about 2.5×10^5 m^3 higher than the no management scenario and carbon sequestration was 1.5×10^5 t higher than that with no management.

The five optimal scenarios with different weights for timber and carbon sequestration can reflect the influence of social preferences on optimal forest management. Because few forests in the study area met the minimum age of harvest initially, the timber harvest volume

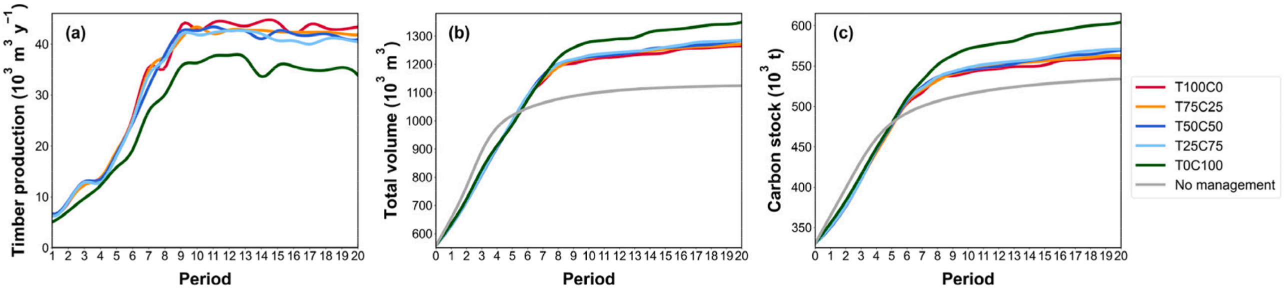

Fig. 2. Forest resource dynamics under different optimal social preference scenarios and the no management scenario. For each scenario over the planning period, the figure presents: (a) timber cutting intensity; (b) existing stand volume; and (c) existing forest carbon stock. T100, T75, T50, T25, and T0 represent the NPV^{timber} weights of 100%, 75%, 50%, 25%, and 0%, respectively. C0, C25, C50, C75, and C100 represent the NPV^{carbon} weights of 0%, 25%, 50%, 75%, and 100%, respectively.

fluctuated significantly in the early period for all optimization scenarios. After natural forest regeneration and an adjustment in plantation age structure, the annual timber production volume stabilized at 35,000 m^3–48,000 m^3 in the late period (Fig. 2a). The existing stand volume and carbon stock also improved over time. The existing stand volume in all optimal scenarios was about 1.8–2.5 times greater than that in the initial period, and the carbon stock was about 1.75 times greater than that in the initial period, which was caused by the growth of trees. With the increase of NPV^{timber} weight in the objective scenarios, an increase in the annual timber production occurred, while the existing stand volume and existing carbon stock decreased. The T0C100 scenario had the lowest harvest volume among the five optimized scenarios, thus having the highest existing stand volume and carbon stock in the later periods. In addition, T100C0 had the highest timber production, but the difference in forest resource dynamics during the planning period was minor when compared with T75C25, T50C50, and T25C25 (Fig. 2b,c).

Fig. 3 shows the total production and total benefits of forest products under different social preference scenarios and the reference scenario across the 100-year planning horizon. In the optimal scenarios with different social preferences, T0C100 maximized the carbon sink and increased the total carbon sink revenue by about 2.5 × 10^6 RMB during the planning time when compared with the other scenarios. In contrast, the total timber production and timber revenue of T0C100 during the planning horizon were both lower than those of the other social preference scenarios. The current carbon price was much lower than the timber price and timber returns always dominated, thus, a relatively small difference in economic gains was observed between the scenarios T25C75, T50C50, T75C25, and T100C0 obtained by changing the NPV^{timber} weight. In these four scenarios, increasing the NPV^{timber} weight only increased the total timber revenue by approximately 8 × 10^6 RMB and decreased the carbon sequestration revenue approximately by 0.2 × 10^6 RMB.

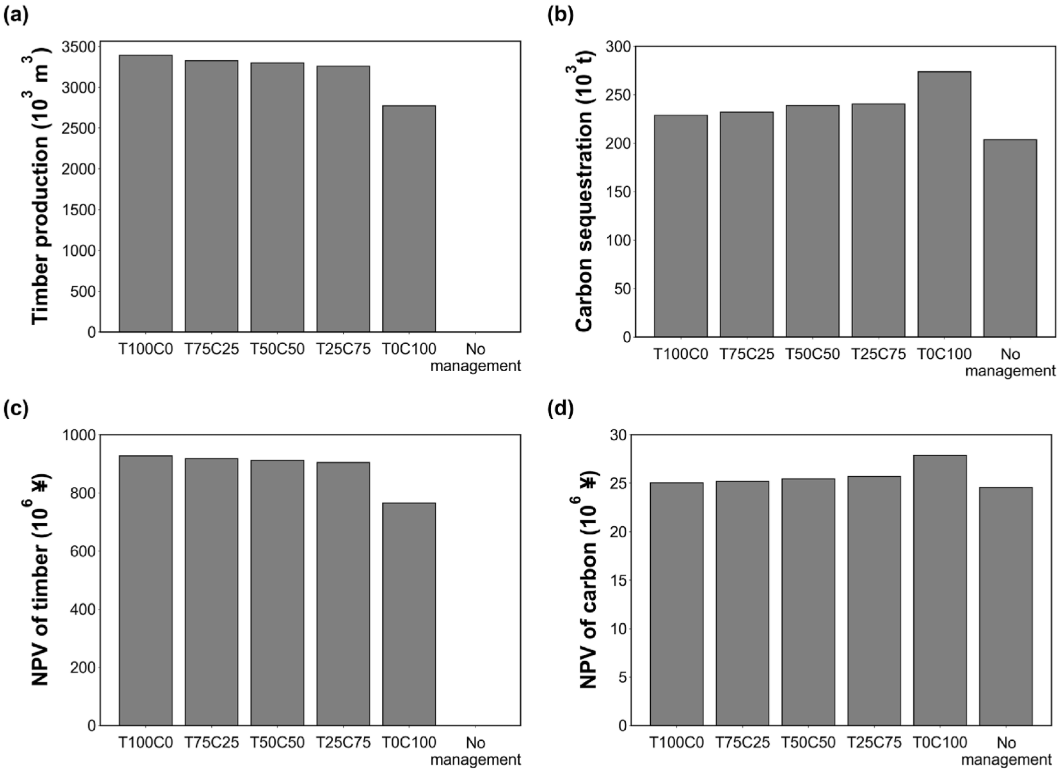

Fig. 3. Total forest product yields and benefits for different optimal social preference scenarios and the no management scenario over 100 years (20 periods of 5 years) for: (a) the amount of timber harvested, (b) the total carbon sequestration, (c) the net present value benefits of timber, and (d) the net present value benefits of carbon sequestration. T100, T75, T50, T25, and T0 represent the NPV^{timber} weights of 100 %, 75 %, 50 %, 25 %, and 0 %, respectively. C0, C25, C50, C75, and C100 represent the NPV^{carbon} weights of 0 %, 25 %, 50 %, 75 %, and 100 %, respectively.

3.3. The sensitivity of forest management to the changes in market prices

We analyzed the sensitivity of forest management, stand volume, and carbon stocks to timber prices by fixing the carbon price (Fig. 4). As expected, timber production increased as the price of timber increased. When the carbon price was fixed at a low price, changing the timber price had little effect on optimal forest management (Fig. 4a,d,g). When carbon prices were fixed at mid-range and high prices, forest management dynamics fluctuated somewhat with timber prices. At mid-range carbon price, the timber production in P_T1P_C2 was about 6,000 m^3 lower than that in P_T2P_C2 and P_T3P_C2, and the existing stand volume and carbon stock were higher than those in P_T2P_C2 and P_T3P_C2 (Fig. 4b, e,h). However, the difference in harvesting intensity between P_T2P_C2 and P_T3P_C2 was very small, the volume in the later period was stable at 1.2×10^6 m^3, and the carbon stock was also stable at 5.5×10^5 t. Fig. 4c, f,i also shows a similar phenomenon. Low timber prices led to low timber yields while maintaining high forest quality, but increasing timber prices at high carbon prices had little impact.

Fig. 5 shows the effects of changing carbon prices on timber production and forest resource quality at a fixed timber price. At the same level of timber prices, timber production decreased as the carbon price increased. When timber prices were fixed at low levels, changing the carbon price would affect optimal forest management. The timber production in P_T1P_C1 was always much higher than that in P_T1P_C2 and P_T1P_C3, and the existing stand volume and carbon stock were the lowest among the three scenarios. The harvesting volume of P_T1P_C3 was slightly lower than that of P_T1P_C2, with less variation in forest resource dynamics. When timber prices were fixed at mid-range and high prices, carbon price changes had relatively little impact on forest management.

Overall, the impacts of timber and carbon prices on timber production and carbon sequestration were small, but the optimal management was relatively more sensitive to carbon price. The NPV^{timber} and NPV^{carbon} differed among these scenarios due to changes in prices (Fig. 6); with the higher the price of the forest product, the higher the economic returns to that product.

4. Discussion

Our study developed a spatially explicit model for forest management planning and analyzed the effects of different social preferences and market price levels on forest management strategies and forest quality. Previous studies have mostly considered a single management approach and have rarely considered optimizing the age structure of forests (Dong et al., 2018; Li et al., 2019; Liu et al., 2017). We optimized timber production and carbon sequestration services at the basic management unit level and obtained the spatial configuration dynamics of different management practices over the next 100 years. All of the optimal scenarios achieved the objective of age structure optimization to attain the normal forest age distribution: all age classes occupying similar areas. In contrast to studies that support no harvesting or less intensive management (Schwenk et al., 2012; Tikkanen et al., 2012), our optimization results emphasized constraints based on classified

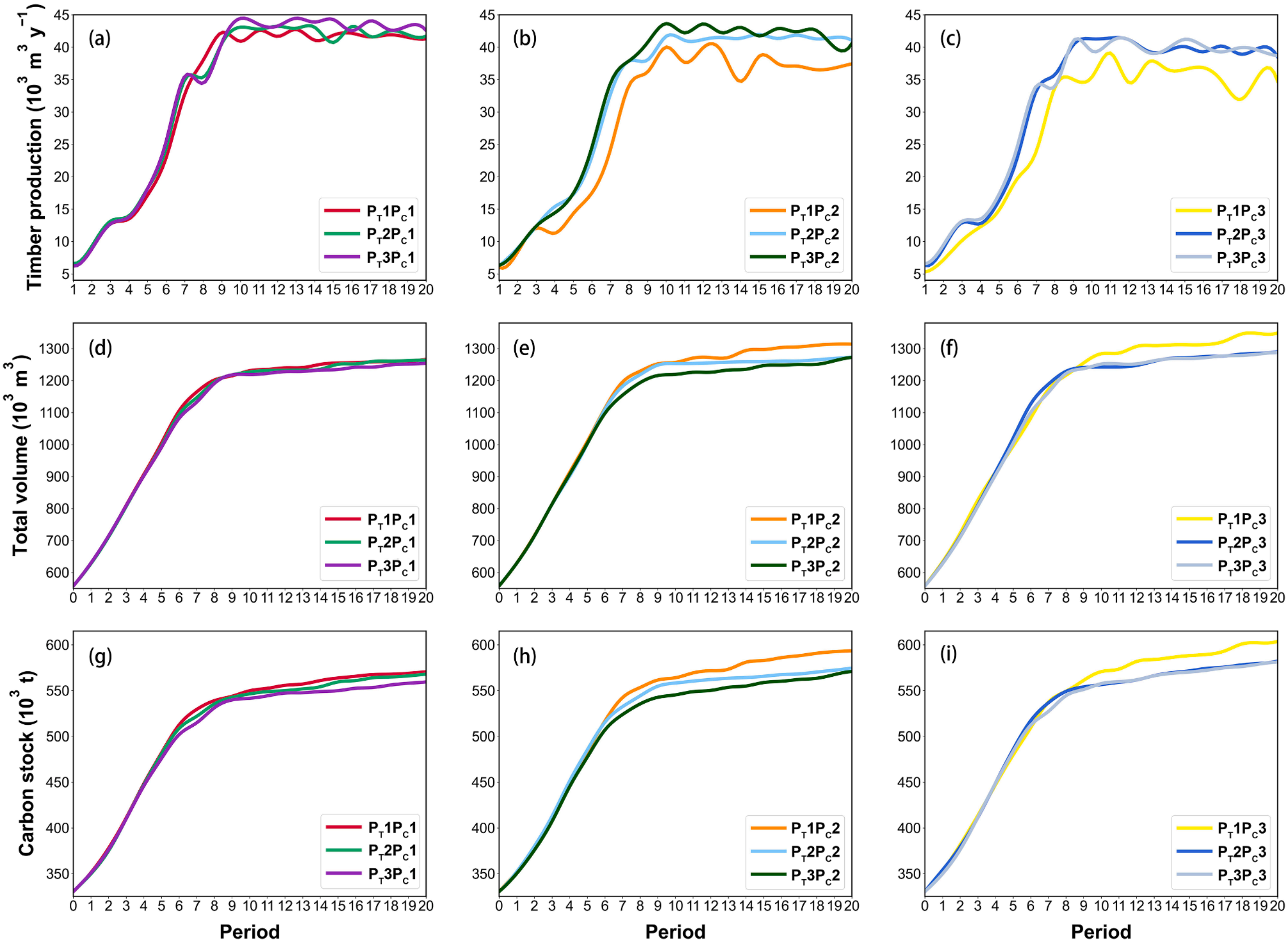

Fig. 4. Impact of changes in timber prices on forest management, stand volume, and carbon stocks under three fixed carbon prices presenting the timber cutting intensity and stand volume and carbon stocks under scenarios where: (a, d, g) the fixed carbon price is low and timber prices vary; (b, e, h) timber prices vary with a mid-range fixed carbon price; (c, f, i) timber prices vary when carbon price is fixed at high level. P_T1, P_T2, and P_T3 represent timber prices at low, mid-range, and high levels, respectively. P_C1, P_C2, and P_C3 represent carbon price at low, mid-range, and high level, respectively.

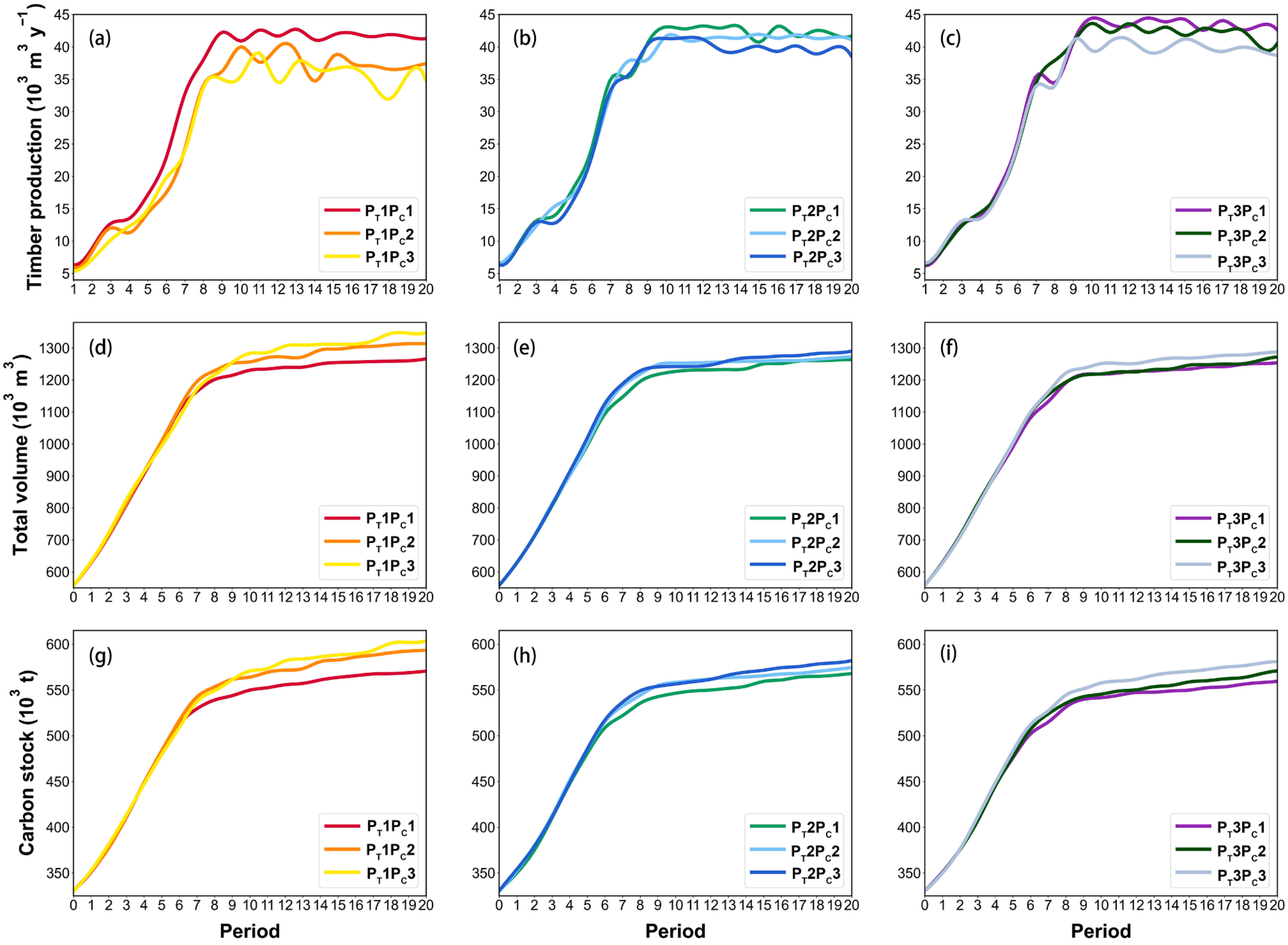

Fig. 5. Impact of changes in carbon prices on forest management, stand volume, and carbon stocks under three fixed timber prices presenting timber cutting intensity and stand volume and carbon stocks under scenarios where: (a, d, g) the fixed timber price is low and carbon prices vary; (b, e, h) carbon prices vary with a mid-range fixed timber price; (c, f, i) carbon prices vary when timber price is fixed at high level. P_T1, P_T2, and P_T3 represent timber prices at low, mid-range, and high levels, respectively. P_C1, P_C2, and P_C3 represent carbon price at low, mid-range, and high level, respectively.

management and normal forest adjustment targets that work to improve long-term forest quality. Therefore, we should determine which management strategies adjust the forest age structure and ensure the sustainable supply of timber and carbon services as much as possible in the future. Our planning model can meet the requirements of sustainable forest management and help forest managers organize management practices effectively.

We found that after the forest age structure was adjusted to that of a normal forest distribution, social preferences had little effect on forest management, stand volume, and carbon stocks. According to optimal growth theory, the consumption expectations would increase once the market interest rate is higher than the time preference of society (Novales et al., 2009). Because the current price of timber is much greater than that of carbon, people are always willing to pay more for wood products, which also reflects that current market mechanisms are unable to capture the value of carbon sequestration in forest management. Policy mechanisms may be required to adjust the behavior of both producers and consumers (Amacher et al., 2009), through increasing carbon sequestration by changes in government policies and by adjusting the carbon price in the trading market. Furthermore, the age structure of the forest under different social weight scenarios stabilized after adjusting to an even distribution after optimal management; so, there was less variation in the age structure. Increased emphasis on forest carbon sequestration under scientific management remains an economically efficient way to mitigate climate change, which will be necessary at the current timber and carbon market price levels.

Markets provide information that reflects the true payment preferences of people in guiding management decisions (Aguilar and Kelly, 2019; Kant, 2004). There is evidence that carbon sequestration costs in forests are low (van Kooten et al., 2009; Yousefpour et al., 2018), and the actual prices of compliance, especially in voluntary markets, are much lower (Ecosystem Marketplace, 2017). Our results indicated the need to increase the carbon price to encourage forest managers to trade carbon sinks, which is also in line with China's current policy that is designed to increase carbon sinks. Some studies suggest that a higher market-based or tax-based carbon price will be necessary for forest management to incorporate the carbon sequestration objectives into management goals. Austin et al. (2020) indicated that for forests to contribute 10 % of the mitigation needed to limit global warming to 1.5 °C, a carbon price of \$281/t CO_2 would need to be reached by 2055. For China, Qin et al. (2017) found that the critical carbon price needed for balancing the timber and carbon objectives in forests may be \$120/t. Dong et al. (2021) proposed a method to find the optimal carbon price that maximizes carbon sequestration in a specific forest in forest management. However, these studies were confined to the northern forests of China. As a typical subtropical forest, the southern forests of China are an essential forestry base with a large number of plantation forests (Ma et al., 2016). Thus, research related to the optimal carbon price in the forest management process in southern China would undoubtedly promote forest multi-objective management and the process of carbon neutralization.

The forest planning model employed in this study could be applied to

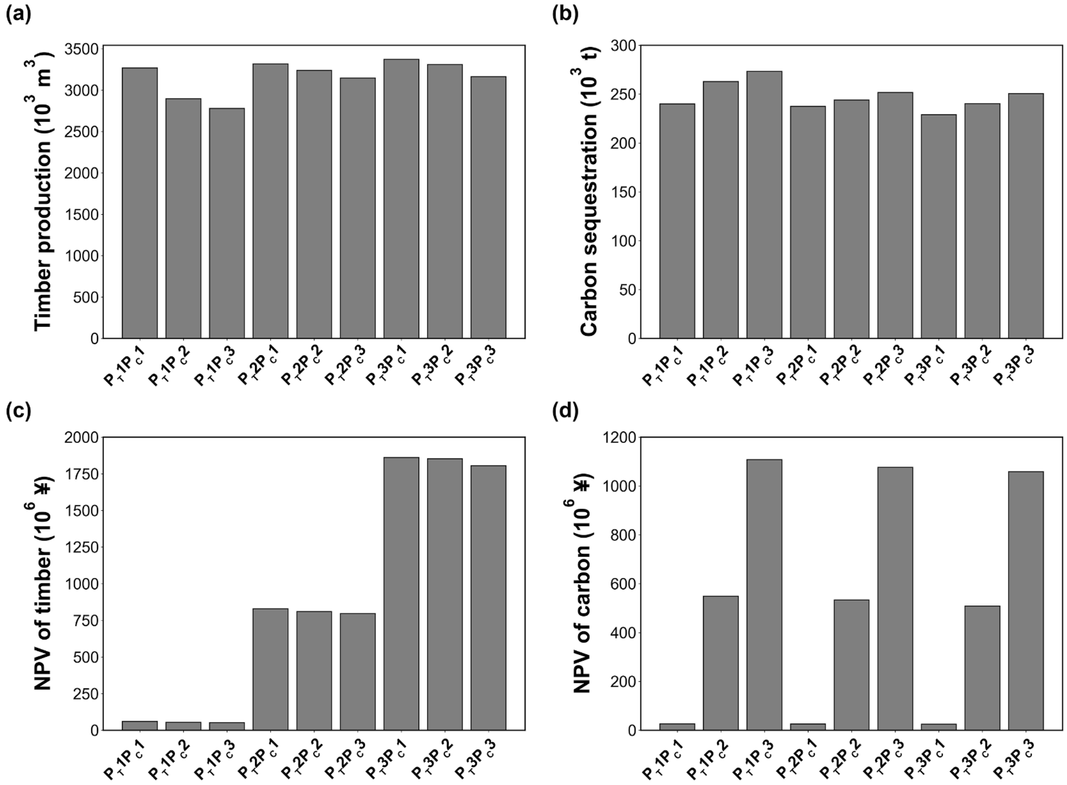

Fig. 6. Total forest product production and total benefits under each market price scenario over 100 years (20 periods of 5 year) for: (a) total timber harvest; (b) total carbon sequestration; (c) net present value benefits of timber; and (d) net present value benefits of carbon sequestration. P_T1, P_T2, and P_T3 represent timber prices at low, mid-range, and high levels, respectively. P_C1, P_C2, and P_C3 represent carbon price at low, mid-range, and high level, respectively.

other forest farms. However, the growth information of local tree species would be required to modify the model appropriately for other farms. In addition, our planning model has some shortcomings. Nutrient removal and reduced organic matter inputs to forest soils through different harvesting practices may affect long-term forest soil fertility and stand productivity, affecting the carbon sink capacity of forest ecosystems (Mack et al., 2014; Powers et al., 2005). At present, such feedbacks remain difficult to quantify using mathematical equations. Therefore, the options for assessing forest carbon in our model are not exhaustive and may include carbon in the soil, understory vegetation, and litter layers in future studies once they can be parameterized in a forest growth model. Additionally, similar to previous studies (Guo and Gong, 2017; Rivière and Caurla, 2021; West et al., 2019), we chose to be conservative with harvested wood products thereby potentially underestimating the potential climate benefits of long-term forest management practices. The management of forests to increase forest heterogeneity is a promising approach that can be designed to meet divergent demands on ecosystem services (Felipe-Lucia, 2021). Therefore, it is appropriate for our model to focus on the response of forest multiclassification units to management strategies and the adjustment of forest structure (promoting natural forest regeneration and adjusting plantation forest to normal forest) during the management process. In the future, further consideration can be given to stand conditions and spatial parameters (e.g., block size, adjacency and open size) to implement more realistic adaptive management strategies and to better understand forest dynamics.

5. Conclusions

Our study provides a spatially explicit forest planning model in support of better sustainable forest management based on scientific constraints. Our planning model focuses on the spatial configuration of different management measures and the dynamics of forest landscape adjustment. The outputs of the model show that forests can be actively managed according to the demand for ecosystem services rather than by simply forbidding timber harvest. Effective management measures that promote the regeneration of natural forests and the adjustment of plantations to the normal forest over a period can positively improve forest quality and ensure subsequent long-term stability in forest quality and support sustainable timber production. Doing so will also help China to better achieve its carbon neutrality target in 2060 because it will effectively improve forest carbon sinks. After a forest is restructured to a reasonable level, social preferences have some influence on optimal management, though the influence is less. From the perspective of market prices, carbon prices rather than timber prices would have a great impact on optimal forest management. The current timber production benefits are much higher than the environmental market value, making it difficult to balance the two values through the optimization of current management practices. Therefore, when designing incentives related to carbon sequestration, government agencies should consider minimizing the gap between the prices of timber and the price of carbon. This implies that an increase in the carbon price could be more attractive for forest stakeholders in support of effectively managing forests and improving stand carbon stocks.

CRediT authorship contribution statement

Wenwen Deng: Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Wenhua Xiang:** Conceptualization, Funding acquisition, Supervision, Data curation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Shuai Ouyang:** Methodology, Formal analysis, Writing – review & editing. **Yanting Hu:** Methodology, Formal analysis. **Liang Chen:** Data curation, Methodology, Formal analysis. **Yelin Zeng:** Data curation, Methodology, Formal analysis. **Xiangwen Deng:** Methodology, Formal analysis. **Zhonghui Zhao:** Methodology,

Formal analysis. **David I. Forrester:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109193.

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