

Article

Modeling Subtropical Forest Changes under Climate Change and Close-to-Nature Silviculture: Is There a Tipping Point in an Uncertain Future in Southern China?

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Abstract: Subtropical forests face pressure from both rapidly changing climate and increasing harvest activity in southern China. However, the interactive effects of various spatial processes on forests are not well known. The objective of the present study was to answer the question of how forest aboveground biomass (AGB) changes under alternative climate change and harvesting scenarios and to determine whether there will be a tipping point for forest AGB before 2300. Our simulation results show that, although total forest AGB did not reach a tipping point before 2300 under possible climate change and harvesting scenarios, the slope of the total forest AGB showed a decreasing trend around 2100 and 2200. Moderate climate warming was conducive to AGB accumulation, except for in the high emissions Representative Concentration Pathway (RCP8.5) scenario. Our results also indicate that timber harvesting is adaptable to the accumulation of biomass under climate change scenarios. Harvesting intensity was a key variable affecting forest AGB more than harvesting frequency. Our findings will help develop more sustainable forest management strategies that can adapt to potential climate change scenarios, as well as determining the effectiveness of implementing alternative forest harvesting policies.

Keywords: forest modeling; climate change; harvesting strategies; aboveground biomass; sustainable logging; subtropical forest

1. Introduction

Global climate change poses a huge threat to forests, and there remains great uncertainty regarding the extent of future climate change, which will greatly depend on current human activities [1,2]. There are ongoing efforts to mitigate the potential effects of global change and to understand the effects of 1.5 °C warming related to global greenhouse gas emission pathways [3], but specific extreme changes may occur in different regions across biomes. Many forests are facing pressure from both rapidly changing climate and increasing timber harvest activity [4]. Global warming has affected forest productivity [5], tree species abundance [6], and spatial distribution [7], while forest loss represents a more pervasive land transformation due to excessive harvesting globally [8]. Such changes have been substantial, but the interactive effects of various spatial processes on forests remains unknown.

As part of the climate change mitigation efforts, many countries have contributed to the greening of the world by changing land-use management strategies [9]. China has been implementing policies, such as the Natural Forest Conservation Program [10] and the Returning Farmland to Forest Program [11].



Some regions have even taken measures to set apart hills for forestry. However, current forest restoration and greening comes at the cost of substantial capital compensation, which will inevitably affect the demand for wood at the regional scale. Prohibiting or restricting logging is beneficial for forest restoration and biomass accumulation in the short term, but whether logging should be completely restricted under potential future climate change scenarios is worth investigating. In addition, forest succession and management are long-term processes, and the following questions are the focus of this paper. How will future climate change affect forest aboveground biomass (AGB)? What is the interaction between climate change and harvesting during forest biomass accumulation?

To address these questions, we introduce the concept of tipping points to quantitative evaluation. A tipping point is derived from the theory of forest resilience and may help to understand the interactions among ecosystems, economics, and climate [12]. Specifically, a tipping point describes a threshold in conditions at which a small change in conditions leads to a strong change in the state of a system [13]. In the sustainable management of forests, this concept is more complicated and refers to the ways in which spatial variation affects the forest ecosystem across multiple spatial and temporal scales [14]. Recently this theory has been applied to understanding ecosystem change under global change. Nepstad et al. applied the concept of a tipping point to examine the interactions among Amazon land uses, forests, and climate [12]. Adams explored the fire-driven tipping points in different vegetation types and noted the tipping points associated with changing climate and human management for managing forests in an uncertain future [15]. In our study, we defined the tipping point as a situation in which there is a decline in the growth of forest AGB in each time interval. We used this concept to determine the potential tipping point at a certain time under the interference from climate change and logging.

The forest landscape disturbance model, LANDIS-II, was used to simulate the effects of climate change and harvesting on forest AGB under various scenarios [16]. LANDIS-II can simulate spatial interactive processes, such as forest succession and natural and human disturbance, and it has been applied to climate change and forest management research globally [16]. For example, Steenberg et al. [2] simulated the combined influence of climate change and timber harvest on tree species distribution and productivity in the forests of central Nova Scotia, Canada. They found that disturbance may drive the range expansion of broad-leaved species, and conifers were favored for pulp production. In addition, other previous studies focused on the effect of, for example, fire and harvesting [17,18], forest carbon management [19], and forest ecosystem services [20]. Forest landscape simulations are helpful for understanding the effect of climate and harvesting on forest AGB, and to formulate corresponding forest management strategies in advance. However, to our knowledge, most previous studies focused on northern forests [21,22], especially in North America [23], with insufficient attention paid to subtropical forests in southern China.

In the present study, we simulated the effects of climate change and harvest on the forest landscape in southern China using the landscape disturbance model LANDIS-II from 2100 to 2300. Our objective was to answer the question of how forest AGB changes under alternative climate change and harvesting scenarios. Moreover, we determined whether there will be a tipping point for forest AGB during our simulation period, and if so, when the tipping point will occur. Our simulation results identify the effectiveness of implementing forest harvesting policies and contribute to the development of sustainable forest management strategies that adapt to climate change.

2. Methods

2.1. Study Area

The study site consisted of an area of 266,700 ha in southern China (Figure 1). The area has a subtropical humid monsoon climate. Soils are mostly homogeneous and dominated by red soil. The topography is characterized by hilly terrain (9–1129 m). The forest covered 1632 km² at a coverage rate of 61.2% in 2010 according to the forest resources inventory of Jiangxi Province. Forest landscape types

included broad-leaved, coniferous, and mixed forest and corresponded to forest management zone I, II, and III, respectively (Figure 1).



Figure 1. Study area with management zones.

The forest type was dominated by second-growth forest and artificial coniferous forest resulting from heavy logging during 1960–1980 [24]. Following this heavy logging, the forest landscape was recovered by planting many coniferous plantations, such as Chinese fir, slash pine, and Masson pine, accounting for more than 60% of the total forested area in 2010. Based on the life span of these dominate tree species, the current forest community was basically in the early stage of succession and most coniferous plantations were close to the harvesting age [7]. With the acceleration of urbanization and townships in China, the demand for land is increasing, and the concomitant climate change will exert intense pressure on the regional forest management [24]. In 2018, the output of wood production was valued at 441 million yuan, which considerably contributed to the local economy [25]. The history of southern forest logging has changed along with China's economy and energy consumption structure [26]. The southern forest is facing some problems, such as pure plantations distribution, unreasonable forest age structure for young forests accounting for a large proportion, lower biodiversity and ecosystem services due to simple forest structure, forest loss caused by soil erosion, the changes in carbon sequestration capacity caused by climate change, and excessive logging or overprotection of forests [27,28]. To adapt to and solve these problems, the current forest management policy of our forest landscape is close-to-nature silviculture. The main goal of forest management is limited to national forest restoration and protection policies, focusing on natural restoration accompanied by artificial management. Therefore, under the overall strategy of natural restoration, adjusting forest management methods may be an effective way to adapt to uncertainties in the future.

2.2. Climate Data

To find a sustainable way to manage forests to mitigate climate change, we considered four predicted climate change scenarios, namely Representative Concentration Pathway (RCP), RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Future climate change data were derived from the multi-model dataset of the Coupled Model Intercomparison Project Phase 5 (CMIP5) framework proposed by the World Climate Research Programme, which was compiled from the projections of 17 general circulation

models (GCMs) that have been averaged, downscaled, and interpolated to a grid of 30" by the MarkSimGCM weather generator [29]. In addition, we considered the current climactic conditions (CC) as the baseline. Under CC, we assumed that the climate would stabilize after the initial simulation year. The climate data of CC were averaged across the past 30 years (1980–2010) and derived from a local ecological station.

Climate data comprised monthly maximum and minimum temperatures and monthly precipitation from 2010 to 2100. From 2100 to 2300, we assumed the climate data held the value at 2100. Although there were high levels of uncertainty, an additional 200 years of simulation is important to identify changes in response to climate change, which would exceed the longevity of most species. The range of increased annual average temperature under the RCP climate change scenarios from 2010 to 2100 was as follows: RCP2.6 (0.1–1.31 °C), RCP4.5 (0.05–2.45 °C), RCP6.0 (0.07–2.78 °C), and RCP8.5 (0.09–4.93 °C). Changes in annual total precipitation differed little between these scenarios, and the range of total precipitation was 1382–1481 mm. CO₂ concentration data were derived from the RCP database [30]. The photosynthetically active radiation observation data were derived from the local ecological station.

2.3. Forest Landscape Model LANDIS-II

The LANDIS-II model is a forest landscape disturbance and succession model simulating forest establishment, competition, growth, decomposition, biomass accumulation, and anthropogenic disturbance [31]. This model can track species–age cohorts to simulate forest landscape change driven by species life-history attributes, species establishment probability, maximum aboveground net primary production (ANPP), and forest disturbance at a specified time step [32,33]. Many extensions have been developed and widely applied to climate change and forest management research. The forest biomass succession extension (Biomass Succession v3.2, eScience, Tokyo, Japan) and timber harvesting extension (Biomass Harvest v3.0, eScience, Tokyo, Japan) were used for addressing the effect of climate change and harvesting on forest biomass in our simulation.

2.4. Model Parametrization

The inputs for LANDIS-II include spatial maps and nonspatial inputs. Spatial inputs were maps for initial forest landscape, ecoregion, forest management, and forest stand. The spatial maps were raster data at 100 m cell size. These spatial inputs were derived from the forestry resource survey data from the subcompartment division in 2010. The nonspatial inputs included life-history attributes of 18 dominant tree species (the species and age cohorts). The species life-history attribute parameters were mainly compiled from the literature, plot investigation data, and consultations with local forestry experts. These parameters were calibrated and verified in previous simulations [7,24,34,35].

In addition, the calculations of ANPP and species establishment probability for each species under specific climate scenarios were derived from the PnET-II for LANDIS-II model. The inputs for PnET-II included climate data, site conditions, and species parameters [36,37]. The setting of these parameters was derived from the RCP database, plot investigation data, the database of flora of China [38], and the literature [34,39,40].

For forest harvesting, forest landscape was divided into three forest management zones based on the managed forest type (Figure 1). The harvest prescriptions were derived from the local forest management practices in the last decade. The input parameters included the percentage of harvesting area, harvesting minimum age, harvesting species, and harvesting cycle. The ranking of the harvesting at a stand was the maximum cohort age. Since the dominant tree species in each management area were different, different logging prescriptions were set up in each management area. For management I and III, the broad-leaved and mixed forest were dominated. Based on our forest management objectives for protection, current harvesting prescriptions set a lower harvesting area ratio. For management II, the harvesting area ratio was set higher because the coniferous plantation was the main supply for local wood production. The minimum harvesting age of different management zones was set according to different tree species attributes (Table 1). In addition, we set four harvesting scenarios to compare the effect of harvesting intensity and harvesting frequency on forest AGB. There was no harvesting occurring in scenario A. Scenario B involved implementing current harvesting prescriptions. Specifically, the harvesting cycle was set to 10 years. The harvest intensity of the management areas I, II, and III were set at 10%, 15% and 5%, respectively. Scenario C involved relatively high intensity logging (five times the current logging area). Scenario D was at a relatively high frequency (shortening the logging cycle 5-fold). In addition, each scenario was set to regenerate after harvesting. The harvesting prescriptions for different harvesting scenarios are shown in Table 2. It needs to be explained that each scenario of each logging management area I is used in scenario B for a single harvest, the remaining 90% area of the management area I will not be harvested.

Management Zones	Harvesting Minimum Ages (Year)	Harvesting Species (Minimum Cohorts Removed)	
Ι	20	Broad-leaved forests: Longpeduncled Alder (>20) Fortune Chinabells (>20) Chinese Sassafras (>20) Chinaberry Tree (>20) Poplar (>20) Crenate Gugertree (>30) Beautiful Sweetgum (>30) Shinybark Birch (>30) Eyer Evergreenchinkapin (>50) Farges Evergreenchinkapin (>50) Faber Oak (>50) Myrsinaleaf Oak (>50) Camphor Tree (>60)	
Ш	15	Coniferous forest: Chinese Fir (>10) Masson Pine (>20) Slash Pine (>10)	
Ш	20	Mixed forest: Chinese Fir (>10) Masson Pine (>20) Camphor Tree (>60) Faber Oak (>50) Farges Evergreenchinkapin (>50) Longpeduncled Alder (>20) Zhennan (>60)	

Table 1. Forest harvesting minimum ages and species in different management zones in Taihe County.

Notes: The cohort stands for tree species are grouped into age classes. The span of an age class is equal to the succession time step (10-years in the simulation).

	Table 2.	Forest	harvesting	prescriptions	for differen	t harvesting	scenarios ii	n Taihe	County.
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Harvesting Scenarios	Management Zones	Harvesting Area (%)	Harvesting Cycle (Year)
	Ι	10%	
В	II	15%	10
	III	5%	
	Ι	50%	
С	II	75%	10
	III	25%	
	Ι	10%	
D	II	15%	2
	III	5%	

Based on the main goal of improving forest management, we simulated total forest AGB for 18 dominant tree species from 2010 to 2300 using a 10-year time step under climate and harvesting scenarios, specifically the five climate scenarios (CC, RCP2.6, RCP4.5, RCP6.0, and RCP8.5), four harvesting scenarios (A: no-harvesting, B: current harvesting, C: high-intensity harvesting, and D: high-frequency harvesting), and the interactions between climate change and harvesting scenarios. In addition, to determine the tipping points of forest AGB under different climate change and forest harvesting scenarios, we calculated the slope of total forest AGB during the simulation period. A negative slope indicated a downward trend in the forest growth rate of AGB in this period. Then, we characterized and mapped forest AGB under the combination of climate and logging scenarios and compared the amount of deforestation in different management zones.

While calibrating and validating the simulation, it is difficult to verify forest landscape dynamics under future scenarios. Therefore, we calibrated the model by comparing with the simulated results at the initial year in the forestry inventory data from 2010 [7]. For forest harvesting, the effectiveness of the model behavior and results was also validated in our previously reported simulations [24,35]. We have carried out extensive field investigations and consulted relevant local forestry experts to ensure parameter rationalization.

3. Results

3.1. Total Forest AGB

Total forest AGB increased under all climate and harvesting scenarios from 2010 to 2300 (Figure 2). However, we also found that the increase rate gradually decreased, especially after 2200. The results demonstrated total forest AGB gradually approaching the maximum forest AGB but without reaching the tipping point until 2300. There was little difference in the change in total forest AGB under the different climate change scenario. Appropriate climate warming was conducive to AGB accumulation. For example, total forest AGB under the current harvesting scenario was ranked as RCP6.0 (28.14 Tg) > RCP4.5 (27.50 Tg) > RCP2.6 (26.46 Tg) > CC (25.83 Tg) in 2300. However, under RCP8.5, the tipping point for total forest AGB appeared around 2080. After which the increase rate of total forest AGB significantly decreased. Total forest AGB under current harvesting and RCP8.5 scenarios was lower than that under the other climate scenarios, reaching 20.61 Tg.

When comparing changes in total forest AGB under different harvesting scenarios (Figures 2 and 3), the results showed that harvesting scenario C had the most timber, indicating that the harvesting area is a more important disturbance parameter affecting forest AGB. Total forest AGB was higher under relatively high-frequency harvesting (scenario D) than under scenario C. Compared with no-harvesting (scenario A), the average difference in total forest AGB under different harvesting scenarios was 2.5 Tg (scenario B), 5.8 Tg (scenario C), and 4.4 Tg (scenario D). In addition, the range of high-frequency harvesting boxes was larger, indicating that the data are relatively discrete. Our results show that a higher harvesting frequency results in a more highly fluctuating total forest AGB curve (Figure 3).



Figure 2. Total forest aboveground biomass (AGB; Tg) under various climate and harvesting scenarios from 2010 to 2300. (a) Climatic conditions (CC), (b) Representative Concentration Pathway (RCP)2.6, (c) RCP4.5, (d) RCP6.0, and (e) RCP8.5. A: no-harvesting, B: current harvesting, C: high-intensity harvesting, and D: high-frequency harvesting.



Figure 3. Differences in total forest aboveground biomass under three harvesting scenarios and no-logging scenarios from 2010 to 2300. (a) Climatic conditions (CC), (b) RCP2.6, (c) RCP4.5, (d) RCP6.0, and (e) RCP8.5. A: no-harvesting, B: current harvesting, C: high-intensity harvesting, D: high-frequency harvesting.

3.2. Phase of Total Forest AGB Accumulation

The results of the slope of total forest AGB showed which phase had a decreasing trend (Figure 4). The rate of increase in total forest AGB decreased year by year and fluctuated. When comparing the differences in the effects of climate change without logging, the slope showed a reduction phase of biomass accumulation around 2190 under CC and RCP2.6. However, this reduction phase disappeared under RCP4.5 and RCP6.0. Under RCP8.5, the range of the reduction phase was larger and advanced

to around 2090, indicating that excessive warming of the climate may accelerate the reduction in forest biomass accumulation and may advance the tipping point.



Figure 4. Slope of total forest aboveground biomass (AGB) from 2010 to 2300. Gray background represents the reduction phase of biomass accumulation. A: no-harvesting, B: current harvesting, C: high-intensity harvesting, D: high-frequency harvesting.

With the intervention of harvesting, the frequency of this gray area that represents the reduction phase of biomass accumulation was higher, and the range was wider. High-intensity and high-frequency harvesting had a greater effect in the early simulation, showing as a significant reduction in biomass accumulation. Around 2100 and 2200, more gray areas appeared under various climatic and harvesting scenarios.

3.3. Spatial Distribution of Forest AGB

The spatial distribution of forest AGB in 2300 is shown in Figure 5. We found that the spatial pattern of forest AGB was consistent with the management zone. Management zone III (mixed forest) had higher forest AGB (>250 t/ha) followed by management zones II (broad-leaved forest) and I (coniferous forest). Climate change had little effect on forest biomass patterns. However, under the RCP8.5 scenario, the forest biomass of management zone II was significantly reduced. The results of forest AGB under different harvesting scenarios showed that high-intensity harvesting had the greatest effect. The average 0–50 t/ha biomass under multiple climate scenarios accounted for 53.96% of the total area of management zone II. The effect of high-frequency harvesting was relatively weak, and the area with biomass of 0–50 t/ha accounted for 42.96% of management zone II.



AGB(t/ha) 🔲 0 📰 0 - 50 🔜 50 - 100 🔜 100 - 150 🔜 150 - 200 🔜 200 - 250 🔜 >250

Figure 5. Spatial distribution of forest aboveground biomass (AGB) under climate change and harvesting scenarios. A: no-harvesting, B: Current harvesting, C: high-intensity harvesting, D: high-frequency harvesting.

The total timber harvesting in different management zones under different climate and harvesting scenarios from 2010 to 2300 is shown in Table 3. There was little difference in the harvesting volume of the three management zones under different climate change scenarios. However, the harvesting volume increased with total forest AGB accumulation. For different management zones, the change in harvesting intensity mainly occurred in management zone II. For example, Chinese fir is an important tree species for local wood production. In this area, the high-intensity harvesting (scenario C) volume was close to four times the current harvesting volume (scenario B), whereas the high-frequency harvesting (scenario D) was twice that of scenario B.

Harvesting Scenarios	Climate Scenarios	Management Zones			
8		I (Tg)	II(Tg)	III(Tg)	
	CC	14.98	18.83	0.82	
	RCP2.6	15.60	18.65	0.84	
В	RCP4.5	16.91	18.38	0.78	
	RCP6.0	17.57	18.96	0.77	
	RCP8.5	16.17	13.61	0.77	
	CC	7.07	82.64	1.22	
	RCP2.6	7.18	81.59	1.21	
С	RCP4.5	7.76	83.43	1.26	
	RCP6.0	8.05	85.83	1.29	
	RCP8.5	7.51	59.30	0.89	
	CC	9.10	37.31	1.13	
	RCP2.6	9.58	36.74	1.16	
D	RCP4.5	11.26	37.19	1.24	
	RCP6.0	11.67	38.62	1.26	
	RCP8.5	8.82	27.23	1.06	

Table 3. Total forest harvesting biomass (Tg) in different management zones under different climate and harvesting scenarios from 2010 to 2300.

4. Discussion

4.1. Interpretation of Results

Our simulations predicted that climate change may increase total forest AGB dependent upon the projected climate scenarios with or without harvesting. Our simulation without harvesting indicated a potential increase in forest AGB from 195% to 301% during the simulation period. For forest landscape, such an increase can be explained as the current total forest AGB having not reached the maximum biomass of each tree species. The coniferous plantations, including Masson pine, slash pine, and Chinese fir, account for a large proportion of our forest landscape, which can compete for more light and nutrient resources, resulting in higher productivity and faster biomass accumulation during early succession. Similar results have also been found in other studies [41].

We found that appropriate climate warming will promote plant growth in our forest landscape. However, we also found that the slope of the increase in total forest biomass was gradually decreasing, especially under the RCP8.5 scenario. Such a decline was also reported by previous studies [7,39,42]. This change was a deterministic consequence of ANPP inputs to LANDIS-II, which in turn were driven by the response of tree species attributes to climate change. This decline can be explained by excessively high temperatures inhibiting photosynthesis and even reducing carbon absorption, consequently leading to a decline in forest productivity [35].

Harvesting also influenced changes in forest AGB over time. Direct climate effects on forest biomass may have a lag time, but harvest activity produces a sudden and significant change [4]. Based on our forest management objectives for protection, the harvesting scenarios were setting as close-to-nature silviculture. Our simulation showed that a relatively stable forest AGB difference formed between harvesting and no-harvesting, which indicates the interaction and adaptability of harvesting and climate change. In addition, different harvesting prescriptions also greatly affect total biomass. Harvesting frequency and intensity driven by human demand and behavior showed significant differences in forest AGB. Our simulation predicted that harvesting intensity was a more critical variable affecting forest AGB. Under the same logging area every 10 years, high-intensity logging has a greater effect on forest biomass than harvesting frequency. Changes in forest AGB may have been due to this high-intensity harvesting, which may have harvested more than the available annual allowable cut. We think that these simulation results could help to develop forest harvesting strategies that can adapt to climate change.

For total forest AGB, our forest landscape did not reach the tipping point under possible climate change and harvesting scenarios during our simulation period. However, our results of the slope of total forest AGB showed a decreasing trend in some years, such as in 2100 and 2200. These decreasing phases of biomass accumulation were all linked to climate warming trends and harvesting. First, the slope of total forest AGB showed a negative trend around 2200 under RCP2.6 and CC scenarios, or 2100 under RCP8.5. This decline can be explained by the limited lifespan of most coniferous tree species. Our simulation calculated forest AGB using the existing biomass, ANPP, and aboveground mortality for each species [43,44]. Aboveground mortality related to species lifespan reduced living AGB. In addition, excessive temperature, such as under RCP8.5, will advance the gray area. Second, the gray area appeared at the beginning of the simulation under harvesting scenarios C and D. This is because there are more forests suitable for harvesting (age or tree species) in the beginning, and the model performs more harvesting AGB during this period. In fact, the process of forest biomass accumulation is a complex process, which is affected by species establishment, forest succession (shade tolerance), climate change, and even forest harvesting. Although the process of biomass accumulation is complicated, we can also conclude that climate warming and human disturbance will inevitably cause the decline of forest biomass, or advance this declining trend.

4.2. Adaptation to Climate Change for Sustainable Forest Management

Adaptive forestry includes sustainable forest management strategies that focus on climate change [45]. Appropriate harvesting strategies can adapt to climate change and support regional forestry economic development [46]. China's current forest management strategy has considerably contributed to the world's greening efforts [9,27]. However, we have to think about whether the current protection measures and forestry policies are sustainable, and how long such protective forestry policies will last. As the demand for local forestry production increases, more economic benefits will surely stimulate changes in harvesting strategies.

We believe that our simulations are significant to the adjustment of forest carbon management strategies. First, our simulations show that appropriate logging will be possible under certain climatic conditions, but in extreme climate scenarios (RCP8.5), such logging will accelerate this decline over the next 200 years. Second, our simulation results can also provide suggestions for how to manage different forest types. Coniferous forests (management II) play a vital role in forest landscape management and occupied a larger area, but the biomass per unit area was insufficient. In fact, the important role of artificial coniferous forest was not only for our forest landscape but also extended to the entire red soil hilly area in southern China [27,47]. Therefore, solving the problem of artificial coniferous forests is an urgent issue for the sustainable management of southern forests. Third, our results also show that high-frequency logging will promote the accumulation of biomass. It is undeniable that such logging will inevitably consume more manpower and financial resources. Therefore, it is particularly important to weigh the timber harvesting volume against market demand.

A limitation of our simulations is the simplification of the complex forest landscape dynamic processes. Our simulations did not consider disturbances such as wind [33], fire [48], and insects because forest fires and insect outbreaks are strictly controlled in Chinese forests. We also did not include species migrating from outside the landscape, CO_2 fertilization, or ozone pollution, which may significantly interact with other global change effects [49,50]. In addition, we recognize that there are some uncertainties in the climate change data, which is averaged, downscaled, and interpolated from multiple GCMs. Owing to the restrictions in data sources, the climate data from 2100 to 2300 are assumed constant. Although there is so much uncertainty after 2100, we consider that analyzing an additional 200 years, which would exceed the longevity of most tree species in subtropical forests, is important to identify species changes [35]. For the results after 2100, we focused on the comparison of biomass changes under different climate scenarios, rather than more accurate prediction. Therefore, we considered these measures to be the trade-offs between the technical and ecological insights [51]. Our alternative harvesting strategies will contribute to dynamic management priorities, market fluctuations, and policy restrictions. Adaptation to climate changes in forest management refers to adjustments in ecological, social, and economic systems in response to the effects of climate change [45]. For future work, we will conduct quantitative trade-off studies between regional harvesting and carbon storage management and strive to identify the relative role of climate change in carbon storage management.

5. Conclusions

Based on our results, we are able answer the question that though the total forest AGB has not reached the tipping point until 2300 under possible climate change and harvesting scenarios, our results for the slope of total forest AGB showed a decreasing trend around 2100 and 2200. Moderate climate warming was conducive to AGB accumulation. However, excessive temperature increase will significantly reduce biomass, such as under the RCP8.5 scenario. Our results also indicate that timber harvesting is adaptable to the accumulation of biomass under various climate change scenarios. Harvesting intensity is a key variable which affects forest AGB more than harvesting frequency. Coniferous forests are favored for timber production in future forest management. We believe that moderate harvesting in our forest landscape will be allowed in the coming decades. Simulating the effects of climate change and close-to-nature silviculture on the forest landscape provides insights into the interaction between climate change and forest management in southern China. Our findings can

guide forest management strategies that adapt to potential climate change scenarios, as well as identify the effectiveness of the implementation of forest harvesting policies.

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