

Characteristic of tradeoffs between timber production and carbon storage for plantation under harvesting impact: A case study of Huitong National Research Station of Forest Ecosystem

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Abstract: The tradeoffs and optimizations of ecosystem services are the key research fields of ecology and geography. It is necessary to maximize the overall benefit of timber production and carbon storage for forest ecological development in China. We selected the Huitong National Research Station of Forest Ecosystem as our study area, and used InVEST model to evaluate timber production and carbon storage quantitatively. The results showed that: (1) While timber production increased with harvesting intensity over the planning horizon, carbon storage decreased. There were tradeoffs between timber production and carbon storage according to the significant negative relationship. (2) While the overall benefit of timber production and carbon storage increased with harvesting intensity, the value of tradeoffs decreased. T1 and T2 scenarios, with harvesting intensity of 10%–20% every 10 years, are the optimum management regimes for the two ecosystem services to gain more benefit and less tradeoffs. (3) The current harvesting intensity in Huitong County was slightly higher than the optimum harvesting intensity. On practical dimension, these findings suggested that obvious objectives are needed to formulate the corresponding countermeasures of tradeoffs, in order to realize the improvement of ecosystem services and the optimization of ecosystem structures.

Keywords: timber production; carbon storage; plantation; tradeoffs analysis; Huitong eco-station

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1 Introduction

Ecosystem services provide manifold products and services for humanity and are a foundation for the survival and development of human society (Fu *et al.*, 2009; Ouyang and Zheng, 2009). Costanza (1997) assessed the total value of global ecosystem services, causing the public to be cognizant of the integrality of ecosystem services and consequently leading to an upsurge in domestic and foreign scholarly research on ecosystem services. In early stages of research, the main focus should be on aspects such as the concept and classification system of ecosystem services (Daily, 1997; de Groot *et al.*, 2002; MA, 2005) and the evaluation of the quality and value of ecosystem services (Ouyang *et al.*, 1999; Nelson *et al.*, 2009; Bangash *et al.*, 2013). With more and more in-depth research, people have discovered that, in the case of increasingly prominent constraints on natural resources, the increase of ecosystem services often leads to a reduction in other services (Tallis *et al.*, 2008), especially those providing services increased at the cost of regulating services, cultural services, and biodiversity loss (Rodríguez *et al.*, 2006; Bennett and Balvanera, 2007). In other words, there is a tradeoff relationship between different services (Li *et al.*, 2013; Zheng *et al.*, 2016; Feng *et al.*, 2016; Wang *et al.*, 2016). Clarifying the relationship and process of tradeoffs between various ecosystem services and maximizing the ecological and economic benefits, in order to provide important scientific basis for regional ecosystem management and sustainable forest management.

The total area of Chinese plantations is 0.79×10^8 hm², which is 28.4% of the total global plantation area and 38% of the total area of forest resources in China, making China the top contributing country to total global plantation area (CSFA, 2014; Payn *et al.*, 2015). Also, the plantation area of China has increased rapidly by 0.44×10^8 hm² during 2005–2013, and in 2100, the addition of carbon storage was predicted 1.5 times of the total forest carbon sinks over the last 20 years. Thus, plantation in China has a huge potential of carbon sequestration in the future (Fang *et al.*, 2015; Liao *et al.*, 2016). With the area of natural forest dwindling, plantations not only have to provide timber, but also take an important responsibility for multiple ecosystem services including carbon storage, water retention, water quality purification, soil conservation and so on. It becomes the crux of sustainable forest management that how to obtain more timber products while preventing the destruction of ecological and environmental quality as far as possible (Baskent *et al.*, 2008).

At present, domestic and foreign scholars have carried out much research on the tradeoffs between providing and regulating services of forest ecosystem and multi-objective forest management. For example, Baskent (2008) used linear programming mathematical models (LP-based models) to maximize the net present value (NPV) of carbon storage, timber production, and oxygen release. Using the LINGO software, Rong (2012) established a programming model with the goal of maximizing the amount of NPV for timber production and aboveground carbon, he also found an increase in carbon storage came at the expense of a reduction in timber production. Fotakis (2012) proposed a type of Spatial Non-Sorting Genetic Algorithm (Spatial NSGA), established a forest management model targeted towards maximization of timber production and minimization of soil erosion, and analyzed the tradeoff relationship between the two. However, the above models are mostly based on complex mathematical methods and modeling frameworks, and forest managers and policy makers have difficulty using them extensively. Bradford and D'Amato (2012) constructed a

simple multi-objective management model, using both overall benefits (means) and tradeoffs (standard deviations) to formulate the optimal management plan in order to provide forest managers and policy makers with a simple and feasible model.

The southern red-soil hilly area is one of the major plantation regions in China, and the plantation stocking volume makes up about 50% of China's total plantation stocking volume, which is a significantly important research area (MWRC *et al.*, 2010; CSFA, 2014). Huitong county of Hunan province is a central production region of one of the main Chinese plantation tree species, *Cunninghamia lanceolata*. We chose the Huitong National Research Station of Forest Ecosystem (Huitong eco-station) with long-term observational data on the Moshao Forest Farm as the study area with two kinds of ecosystem services, timber production and carbon storage, as the typical representatives of providing and regulating services, respectively. By setting up forest management regimes with different harvesting intensities, analyzing trends during the planning period of providing and regulating services, and calculating the overall benefit and tradeoffs of them under different management regimes, we can select a forest management program that will maximize the overall benefits of local forest ecosystem, thus helping us for the formulation of tradeoffs strategies to consider the sustainable management of plantations in southern China.

2 Study area

The Moshao Forest Farm in Huitong Eco-station, with a total area of 98.24 hm², is situated on the Yunnan-Guizhou Plateau towards the transitional zone of the hilly region south of the Yangtze River with low mountain landform at an elevation of 300–580 m and a slope between 25 and 35 degrees; the terrain shows a gradual decline from northwest to southeast. The area belongs to a humid subtropical monsoon climate. The average annual temperature from 1998–2013 was 16.36°C, and the average annual precipitation is 1137.32 mm (according to the observational data from Huitong eco-station's automatic weather station). The soil is mountainous yellow soil, and the soil layer thickness is generally 80 cm. According to eco-geographical regionalization, the study area lies in the mid-subtropical humid zone of the Hunan-Guizhou plateau's mountainous region in a broad-leaved evergreen forest region. The natural zonal vegetation mainly consists of *Castanopsis* and *Lithocarpus*, subtropical evergreen broad-leaved forests (Zheng *et al.*, 2008).

The forest vegetation map of the study area was compiled based on from a Pléiades satellite image with a 0.5 m × 0.5 m resolution. The forest farm contains natural forests of 51.68 hm² and plantations of 46.56 hm². The dominant species are *Castanopsis fargesii*, *Cyclobalanopsis glauca* and *Machilus pauhoi* in natural broad-leaved forest, *Cunninghamia lanceolata* and *Pinus massoniana* in the planted forest (Figure 1).

3 Data and methods

Synthetically using the tradeoffs method provided by Bradford and D'Amato (2012) and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, we proposed a conceptual framework of forest ecosystem service tradeoffs between providing service (timber production) and regulating service (carbon storage) under the influence of harvesting (Figure 2). First of all, we selected typical forest farm and evaluated timber production and

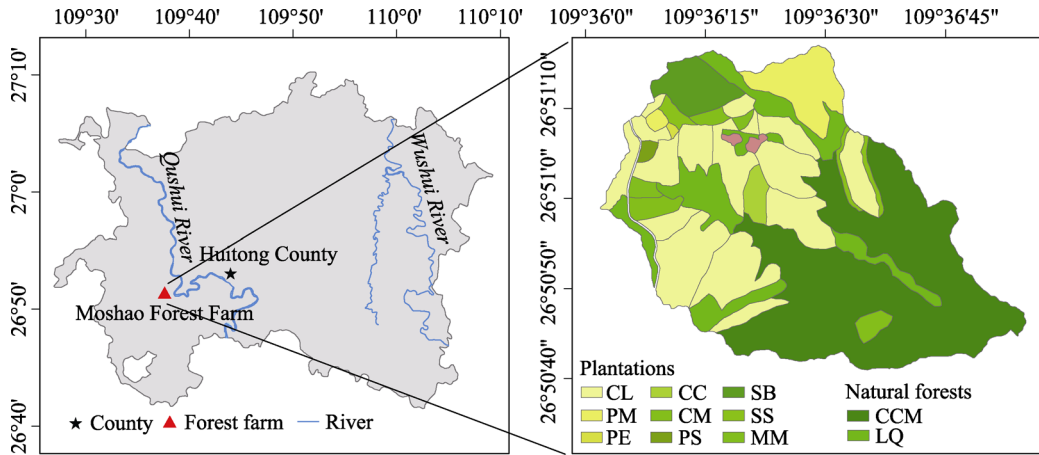


Figure 1 Location and forest vegetation map of Moshao Forest Farm in Huitong eco-station. CL=*Cunninghamia lanceolata*, PM=*Pinus massoniana*, PE=*Pinus elliottii*, CC=*Cunninghamia lanceolata* and *Cinnamomum camphora*, CM=*Cunninghamia lanceolata* and *Michelia macclurei*, PS=*Pinus massoniana* and *Schima superba*, SS=*Schima superba*, MM=*Michelia macclurei*, LQ=*Liquidambar formosana* and *Quercus fabri*, SB=*Schima superba* and *Bretschneidera sinensis*, and CCM=*Castanopsis fargesii*, *Cyclobalanopsis glauca* and *Machilus pauhoi*.

carbon storage quantitatively by InVEST model. Then, we constructed several tradeoffs scenarios of different harvesting intensities, tradeoffs method based on mean and standard deviation was used to clarify the tradeoffs mechanism between providing and regulating services. Finally, we revealed the tradeoffs characteristics of multiple ecosystem services under different harvesting intensities.

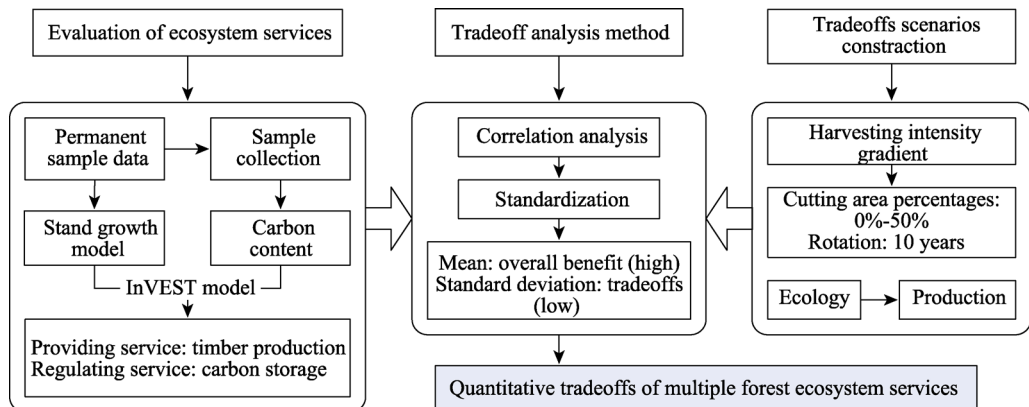


Figure 2 Conceptual framework of forest ecosystem service tradeoffs

3.1 Stand growth model simulation

Because growth rate of trees shows a “slow-fast-slow-end” trend with increasing age, the S-shaped curve can be used to describe it (Vonbertalanffy, 1957; Richards, 1959; Zeide, 1989).

From 1983–1990, Moshao Forest Farm in Huitong eco-station on the established different types of plantations, and set the fixed sample plot size to 10 m × 20 m. Since the establishment of the stand, the diameter and height of the trees within the plots have been measured

year after year. Our research chose the *Michelia macclurei* forest planted in 1983, the *Cunninghamia lanceolata* forest planted in 1983, the *Cunninghamia lanceolata-Michelia macclurei* mixed forest planted in 1983, the *Schima superba* forest planted in 1987, the *Pinus massoniana* forest planted in 1987, the *Pinus massoniana-Schima superba* mixed forest planted in 1987, the *Cunninghamia lanceolata* forest planted in 1990, and the *Cunninghamia lanceolata-Cinnamomum camphora* mixed forest planted in 1990. These eight forests were used to simulate the growth equations of the main tree species on the Moshao Forest Farm. Based on these permanent sample plot data, we tried to use power function equation, logarithmic equation, logistic equation, Richards equation and S-curve equation to fit stand growth model, and we found that S-curve equation ($y=e^{b0+b1/x}$) (with the highest significance level) was a logical choice for the stand growth equations in this study.

First, the biomass of each species' various organs (stem, branch, leaf, bark, root) was calculated year after year in accordance with the biomass models of different tree species (Sun *et al.*, 2012). Then, the S-shaped curve equation was applied to fit the annual changing curve of the biomass of each species' various organs, thereby obtaining the growth models (Table 1).

Table 1 Growth models of main tree species of Moshao Forest Farm in Huitong eco-station

Forest types	Organs	Stand growth models	Correlation coefficient and significance level	Number of trees of stand plots
<i>Pinus massoniana</i>	Stem	$y=e^{5.666-33.687/x}$	$R^2 = 0.994, P < 0.001$	42
	Branch	$y=e^{4.851-42.961/x}$	$R^2 = 0.994, P < 0.001$	
	Leaf	$y=e^{4.557-45.786/x}$	$R^2 = 0.994, P < 0.001$	
	Bark	$y=e^{3.404-33.639/x}$	$R^2 = 0.994, P < 0.001$	
	Root	$y=e^{4.911-39.678/x}$	$R^2 = 0.994, P < 0.001$	
<i>Michelia macclurei</i>	Stem	$y=e^{5.485-27.760/x}$	$R^2 = 0.991, P < 0.001$	37
	Branch	$y=e^{4.626-26.297/x}$	$R^2 = 0.991, P < 0.001$	
	Leaf	$y=e^{3.191-24.898/x}$	$R^2 = 0.991, P < 0.001$	
	Bark	$y=e^{3.340-23.831/x}$	$R^2 = 0.991, P < 0.001$	
	Root	$y=e^{4.536-23.927/x}$	$R^2 = 0.991, P < 0.001$	
<i>Schima superba</i>	Stem	$y=e^{5.025-32.623/x}$	$R^2 = 0.990, P < 0.001$	37
	Branch	$y=e^{4.191-30.904/x}$	$R^2 = 0.990, P < 0.001$	
	Leaf	$y=e^{2.632-25.874/x}$	$R^2 = 0.991, P < 0.001$	
	Bark	$y=e^{2.946-28.006/x}$	$R^2 = 0.990, P < 0.001$	
	Root	$y=e^{4.140-28.119/x}$	$R^2 = 0.990, P < 0.001$	
<i>Cunninghamia lanceolata</i>	Stem	$y=e^{5.462-22.408/x}$	$R^2 = 0.982, P < 0.001$	20
	Branch	$y=e^{3.606-23.411/x}$	$R^2 = 0.982, P < 0.001$	
	Leaf	$y=e^{4.692-18.100/x}$	$R^2 = 0.982, P < 0.001$	
	Bark	$y=e^{3.248-15.805/x}$	$R^2 = 0.982, P < 0.001$	
	Root	$y=e^{2.459-10.460/x}$	$R^2 = 0.975, P < 0.001$	
<i>Cinnamomum camphora</i>	Stem	$y=e^{6.810-43.013/x}$	$R^2 = 0.994, P < 0.001$	24
	Branch	$y=e^{5.881-40.748/x}$	$R^2 = 0.994, P < 0.001$	
	Leaf	$y=e^{4.450-39.484/x}$	$R^2 = 0.991, P < 0.001$	
	Bark	$y=e^{4.478-36.926/x}$	$R^2 = 0.994, P < 0.001$	
	Root	$y=e^{5.678-37.075/x}$	$R^2 = 0.994, P < 0.001$	

3.2 Assessment of ecosystem services

3.2.1 Timber production

We chose the Timber module of InVEST model to calculate timber production at Moshao Forest Farm. The InVEST model is the most widely applied ecosystem service evaluation model and has been successfully applied to multiple regions, including China, the Mediterranean, Sumatra, and the USA (Bangash *et al.*, 2013; Delphin *et al.*, 2013; Bhagabati *et al.*, 2014; Pan *et al.*, 2015). The following equation was used to calculate timber production volume:

$$TVolume = \sum_{x=1}^n Parcl_area_x \times \frac{Perc_harv_x}{100} \times Harv_mass_x \times \frac{1}{D_x} \quad (1)$$

where *TVolume* is the total timber production volume of the *x*th forest (m^3); *Parcl_area_x* is the area of the *x*th forest (hm^2); *Harv_mass_x* is the stem biomass of the *x*th forest (t/hm^2); and *D_x* is the average timber density of the *x*th forest (g/cm^3).

The stem biomass for each forest type can be calculated with growth models above-mentioned (Table 1). Then, the biomass of timber production was converted to the forest stock volume using the average basic density of the timber. The average basic density of timber was found in the timber density table of the major tree species (RIWI and CAF, 1982).

3.2.2 Carbon storage of trees

In July 2014, 131 samples containing stem, branch, leaf, bark, and root were collected for the dominant tree species of each forest stand (the top three, ranked by quantity); each sample was about 300 g. The samples were dried and then ground; the organic carbon content was subsequently determined using the potassium dichromate sulfuric acid oxidation method (Dong *et al.*, 1997).

The amount of carbon storage in the tree layer (stem, branch, leaf, bark, and root) was determined by multiplying the biomass per unit area by the corresponding carbon content, which was then multiplied by the stand area (Equation 2). The tree layer biomass of each component was obtained according to the tree age and the growth model; the carbon content of different organs was observed data.

$$TOC = \sum_{i=1}^n (B_i \times C_i) \times \frac{1}{1000} \quad (2)$$

where *TOC* is the carbon density of tree layer (t/hm^2); *B_i* is the biomass per unit area of the *i*th component; *C_i* is the carbon content of the *i*th component; 1/1000 is the coefficient of unit conversion.

3.3 Methods for ecosystem services tradeoffs

Tradeoffs relationship between timber production and carbon storage was quantified according to the conceptual framework of forest ecosystem service tradeoffs (Figure 2). First, using the Person correlation coefficient method to analyze the interactive relationship between the two ecosystem services. Second, because each ecosystem service dimension is not the same, in order to calculate the overall benefit and tradeoffs of multiple ecosystem services, data must be standardized, making the data range between 0 and 1 (Equation 3). The

overall benefit of multiple ecosystem services is the average value of the ecosystem services after standardization. The magnitude of the tradeoffs between more ecosystem services is represented by a standard deviation. Finally, with the help of the diagonal graphic method, the optimal management regime should be determined by intuition. The objective of multi-objective forest management in this study is to maximize the overall benefit of timber production and carbon storage and to minimize the tradeoffs.

$$B_A = \frac{A - A_{\min}}{A_{\max} - A_{\min}} \tag{3}$$

where B_A is the benefit for ecosystem service A after standardization; A is the benefit for ecosystem service A ; A_{\max} and A_{\min} are the maximum value and minimum value for ecosystem A , respectively.

Figure 3a shows the overall benefit of timber production and carbon storage. The point on the diagonal line $y = -x + 1$ gives 0.5 as the overall benefit: the closer to the upper right corner, the higher the overall benefit. Figure 3b shows the tradeoffs between timber production and carbon storage. The point on the diagonal line $y = x$ indicates the two are equal, so the tradeoffs is zero. On the upper left part of the diagonal line, carbon storage is greater than timber production. On the lower right corner of the diagonal line, timber production is greater than carbon storage. The closer the distance to the diagonal line, the smaller the tradeoffs. Therefore, combining Figures 3a and 3b, we can conclude that the closer to the upper right corner and the closer to the diagonal line $y = x$, the higher the overall benefit of timber production and carbon storage, the smaller the tradeoffs.

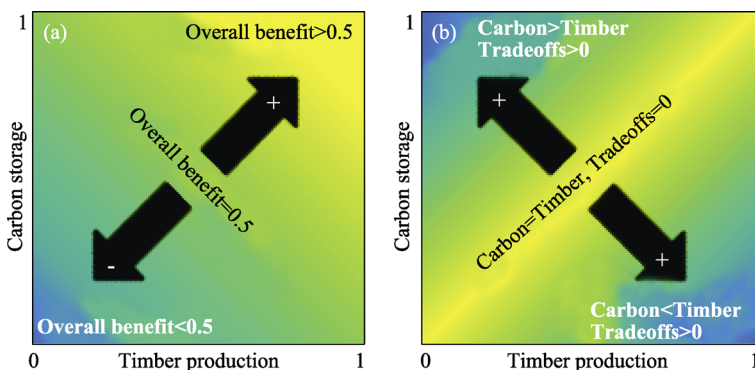


Figure 3 Illustration of overall benefit and tradeoffs between timber production and carbon storage (Modified from Bradford and D'Amato, 2012)

3.4 Forest management regimes identification

The previous studies found that provisioning services first increase and then decrease with the amplification of harvesting intensity; the regulating services and the supporting services gradually decrease; when the harvesting intensity remains at a low level, the cultural services of the forest ecosystem are the greatest (Braat and ten Brink, 2008). The realization of the sustainable management of forests must take environmental protection, biodiversity enhancement, economic benefit, and social function into consideration (Baskent *et al.*, 2008). Therefore, tradeoffs scenarios of different management regimes were created by considering harvesting intensity gradient. With the amplification of cutting intensity, the production function of the forest increased, whereas the ecological function gradually decreased.

Based on the statistical data came from Forestry Department in Huitong County from 2010 to 2014, the local harvesting intensity is harvesting 2.26% of the plantation area every year, which is approximate equivalent to harvesting 22.6% of the plantation area every 10 years. By extending the local harvesting intensity, six management regimes were created to represent combinations of possible management criteria: cutting area percentages of 0%–50%; rotation is 10 years; harvesting principles of small-area clear-cutting ($\leq 5 \text{ hm}^2$) (Table 2). The harvesting intensity increased from T0 to T5, and each of these management regimes was applied over a 100 year planning horizon. According to government regulations (Technical Survey and Design Requirements for the Forest Harvesting Area in Hunan Province, China), cutting rotation of all plantation species were regulated as follows: 18 years for *Pinus elliottii*, 21 years for *Cunninghamia lanceolata*, 26 years for *Pinus massoniana* and *Schima superba*, 41 years for *Cinnamomum camphora* and *Michelia macclurei*.

Table 2 Potential management regimes of Moshao Forest Farm in Huitong eco-station

Management regimes	Cutting area percentages/%	Rotations/year	Harvest principles
T0	0		
T1	10		
T2	20		
T3	30	10	small-area clear-cutting (cutting areas $\leq 5 \text{ hm}^2$ and interval areas between cutting areas \geq cutting area)
T4	40		
T5	50		

4 Results

4.1 Variations in timber production and carbon storage due to harvesting time

Under different management regimes, timber production and carbon storage showed different change characteristics dependent upon harvesting time (Figure 4). Under the T0 management regime, without harvesting activities, timber production was zero; with the natural growth of the forest, the tree biomass gradually increased. Carbon storage also showed an S-shaped curve. Changes in timber production and carbon storage are closely related to forest growth; consequently, they increase with increased harvesting intensity. From harvesting 10% of the total area every 10 years to harvesting 50% of the total area every ten years, the two kinds of ecosystem services show different change characteristics depending on the harvesting time. Under the T1 and T2 management regimes with relatively low harvesting intensities, timber production increased slightly with harvesting time, and carbon storage still showed an S-shaped curve over time. Under the T4 and T5 management regimes with relatively high harvesting intensities, timber production and carbon storage both showed a downward trend in correlation with the harvesting time. Under the T3 management regimes, timber production and carbon storage were relatively stable in correlation to time. Corresponding to increases in harvesting intensity, the fluctuation in timber production gradually became more and more severe.

4.2 Variations in timber production and carbon storage due to harvesting intensity

There was a significant correlation between the two ecosystem services and the harvesting

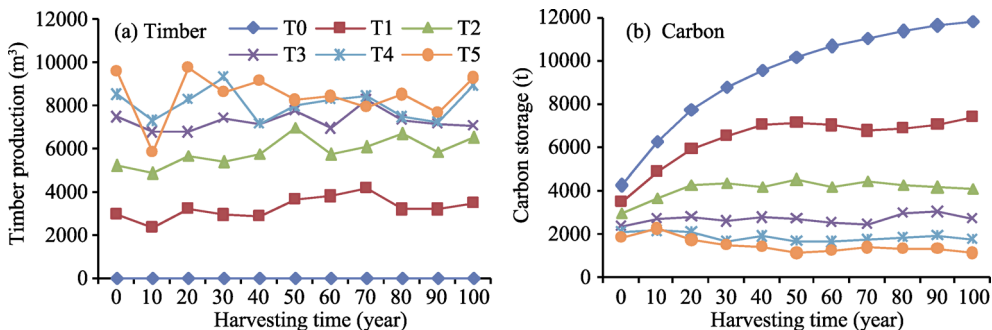


Figure 4 The variance of timber production (a) and carbon storage (b) with harvesting time

intensity for each of the 10 years in which the range of harvesting intensity produced a total harvested area of 0%–50% (Figure 5). Due to the impact of forest growth, timber production and carbon storage showed a curve variation in relation to harvesting intensity. Timber production increased with the increase of harvesting intensity, while carbon storage decreased. The forest’s timber production service was the highest under the T5 management regime, while the forest’s carbon storage service was the highest under the T0 management regime. Timber production and carbon storage were significantly negatively correlated ($R=-0.907$, $P<0.001$) and showed a strong tradeoffs relationship.

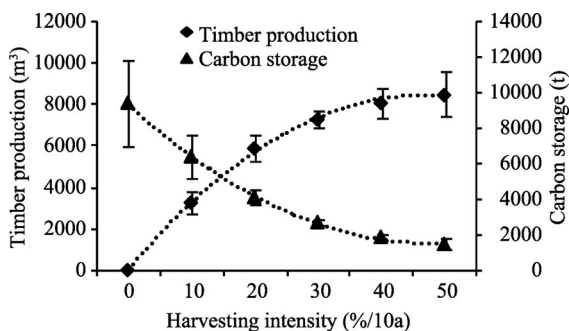


Figure 5 The relationship between harvesting intensities and timber production (a) and carbon storage (b). Error bar represents the standard deviation.

Binomial regression equation of timber production with harvesting intensity:

$$y = -3.873x^2 + 359.719x + 51.044 \quad (R^2 = 0.999, P < 0.001)$$

Binomial regression equation of carbon storage with harvesting intensity:

$$y = 3.363x^2 - 323.710x + 9319.317 \quad (R^2 = 0.999, P < 0.001)$$

4.3 Overall benefit and tradeoffs of timber production and carbon storage

The average overall benefit of timber production and carbon storage was 0.43 ± 0.07 , and the average tradeoffs value was 0.41 ± 0.19 . With the lack of harvesting activities under the T0 management regime, the overall benefit and the tradeoffs value both increased with the increase of harvesting time and reached the maximum in 100 years. Under the T1 and T2 management regimes, the overall benefits of timber production and carbon storage in the first 50 years showed an increasing trend corresponding to the harvesting time, and the changes were steady and unvaried after 50 years. The overall benefits under the T3, T4, and T5 management regimes and the tradeoffs values under the T1–T5 management regimes fluctuated in correlation to the harvesting times and did not show a significant upward or downward trend.

In this study with six management regimes of different intensities, the overall benefit of timber production and carbon storage increased with increased harvesting intensities. The overall benefit of the T0 management regime was the lowest, with an average of 0.39 ± 0.11 . The overall benefit of the T5 management regime was the highest, with an average of 0.45 ± 0.05 . The tradeoffs values of the two regimes correlate to the harvesting intensity, first falling and then rising; going from big to small, the values were as follows (Figure 6): T5 (0.59 ± 0.09) > T0 (0.55 ± 0.16) > T4 (0.54 ± 0.06) > T3 (0.42 ± 0.04) > T2 (0.23 ± 0.04) > T1 (0.12 ± 0.04).

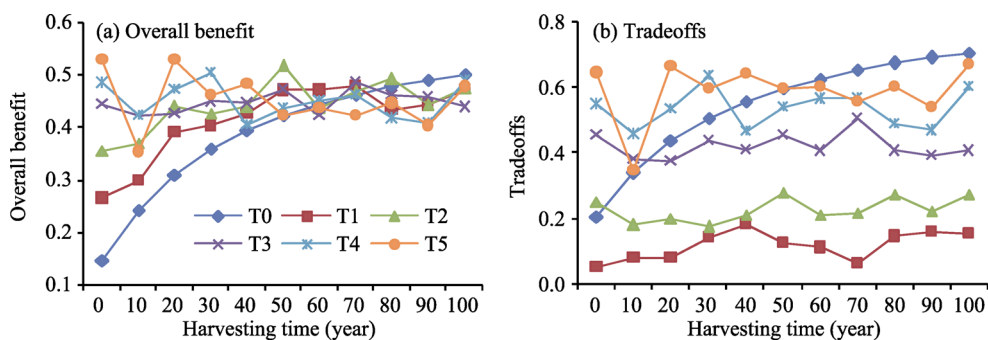


Figure 6 The overall benefits (a) and tradeoffs (b) of timber production and carbon storage

5 Discussion

5.1 Tradeoffs between providing and regulating services

The numerous ecosystem services that human society relied on are not independent of each other, and that the relationships between them are tradeoffs and synergies of different degrees (Rodriguez *et al.*, 2006; Bennett *et al.*, 2009). Our study found that tradeoffs between providing services (timber production) and regulating services (carbon storage) existed at regional scale under the impact of forest harvesting management. The increase of timber production was at the expense of forest loss, which resulting in the reduction of carbon storage directly. These results are consistent with Feng *et al.* (2016) and Wang *et al.* (2017), the implementation of China's Grain-for-Green Programme (GFGP) increased forest area, leading to increase of regulating services such as soil conservation and carbon storage, and decrease of providing services such as water yield. However, the interactive relationships were more complex in the study of ecosystem services based on the present situation. For example, synergies relationship instead of tradeoffs between water providing and regulating services were found in some studies (Bai *et al.*, 2011; Qiu and Turner, 2013), and the relationships among non-production services were not always synergies (Dixon *et al.*, 1993). It proved that the relationships among ecosystem services were complex, and the tradeoffs and synergies may be driven mainly by regional differences and human activity (Raudsepp-Hearne *et al.*, 2010).

5.2 Identifying the multi-objective forest management regime

The six management regimes all fell on the lower left corner of the diagonal line, $y=-x+1$. The overall benefit was < 0.5 , and the differences in overall benefits between the different

management regimes were relatively small (Figure 7a). Two of the management regimes, T0 and T1, were situated on the upper left corner of the diagonal line, $y=x$, where the carbon storage was greater than timber production. This illustrated that a relatively low harvesting intensity was beneficial to the accumulation of forest carbon storage, while simultaneously limiting the development of timber production. The T2–T5 management regimes were situated on the lower right corner of the $y=x$ diagonal line, where the timber production was greater than carbon storage. This illustrated that under a relatively high harvesting intensity, the ability of the forest to provide timber was comparatively strong. However, due to the decrease in the forest stand, carbon storage services also subsequently decreased. Looking at the range of the diagonal line, $y=x$, the tradeoffs between timber production and carbon storage under the T1 and T2 management regimes was relatively small (Figure 7b). Combining the results of the overall benefit and tradeoffs, it may be concluded that the tradeoff relationship between timber production and carbon storage is obvious, with comparatively low overall benefit, and the management regimes that are relatively suitable for the coordinated development of these two ecosystem services are the T1 and T2 management regimes.

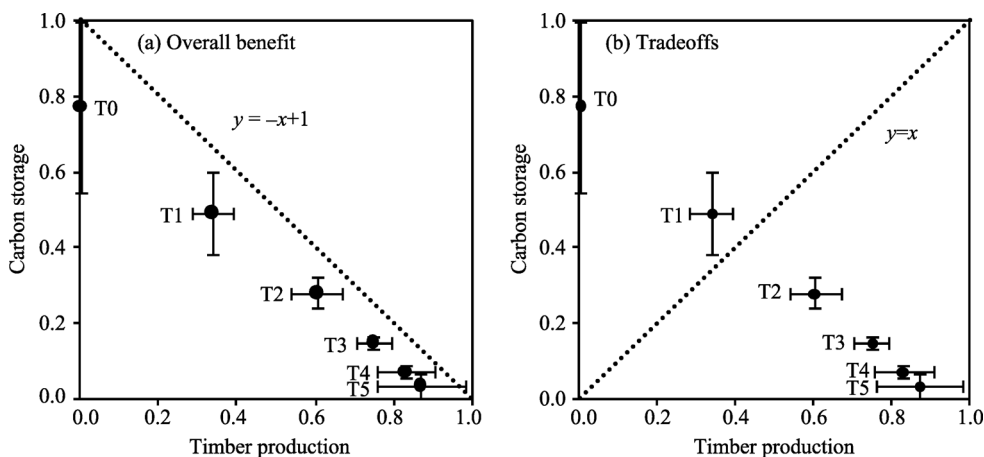


Figure 7 The relationship between individual benefits of timber production and carbon storage. Error bar represents the standard deviation.

By comparing results of multiple forest management regimes and the investigation of local harvesting regime, the deviation of ecosystem services tradeoffs method was used to quantitatively analyze the overall benefit and tradeoffs between multiple ecosystem services, then the tradeoffs mechanism between timber production and carbon storage was exhibited with the help of the diagonal graphic method. We found that the current harvesting intensity of Huitong County (22.6% of the total area of plantations harvested every 10 years) was slightly higher than the optimum harvesting intensity. In future development of plantations, more benefits from forests can be obtained by reducing the harvesting intensity appropriately. Using the tradeoffs method provided by Bradford and D'Amato as a reference, we proposed a conceptual framework of forest ecosystem service tradeoffs between timber production and carbon storage which can achieve the quantitative tradeoffs between providing and regulating services. Therefore, according to our conclusions, forest management objectives should be made clear, then by using the deviation of ecosystem services tradeoffs method,

corresponding countermeasures of tradeoffs will be formulated in order to realize the improvement of ecosystem services.

5.3 Limitations and future research prospects

We simulated future ecosystem services, assuming that tree growth was only influenced by harvesting activities, and the regeneration method was artificial regeneration. However, climate change and forest fires were also main factors that affect forest growth. Future research should consider changes in more factors and try to simulate the change characteristics of forest ecosystem services under naturally regenerating circumstances, focusing on doing large-scale simulations on plantations in southern China, then realizing ecosystem services tradeoffs across space. In the simulation of the tree growth equation, the interference of harvesting, climate change, fire, and other factors (Wang, 2013) should be taken into account to reduce error in the simulation results. In addition, the key point of sustainable forest management is to try to give full play to the ecological functions of the forest while simultaneously acquiring forest timber products (Baskent *et al.*, 2008). We chose timber production and carbon storage to analyze the tradeoffs between providing and regulating services. The focus of future work is to use more forest ecosystem services (such as water conservation, soil retention, windbreak and sand fixation, and biodiversity, etc.) as multi-objective management targets to create a more comprehensive balance between forest production and ecological functions.

6 Conclusions

Setting the forest providing service (timber production) and regulating service (carbon storage) as forest management objectives, using Moshao Forest Farm in Huitong eco-station as the study area, and looking at the overall benefit and tradeoffs of timber production and carbon storage, optimal management regimes for local forest growth rules could be clearly determined. A scientific basis for the sustainable management of the plantations of the red-soil hilly region of southern China can be provided. The main conclusions are as follows:

(1) As harvesting intensifies, timber production continuously increases, and carbon storage continuously decreases. Due to the impact of forest growth, the two show a curve variation in relation to harvesting intensity. There is a significant negative correlation between timber production and carbon storage ($R=-0.907$, $P<0.001$) and also a strong tradeoffs relationship.

(2) The overall benefit of timber production and carbon storage increases as harvesting intensity increases. The T5 management regime with a harvesting intensity of 50% every 10 years has the highest overall benefit; the tradeoffs correlates to the harvesting intensity, first falling and then rising. The T1 management regime with a harvesting intensity of 10% every 10 years has the lowest tradeoffs value. The management regimes with harvesting intensities between 10%–20% every 10 years can realize the coordinated development of timber production and carbon storage.

(3) The current harvesting intensity in Huitong County is above the optimal harvesting intensity, more benefits from forests can be obtained by reducing the harvesting intensity appropriately. While drafting a future forest management regime for southern China, forest

management objectives should be made clear, and formulating corresponding tradeoffs countermeasures in order to achieve forest ecosystem services enhancement and structure optimization.

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References

- Bai Y, Zhuang C W, Ouyang Z Y *et al.*, 2011. Spatial characteristics between biodiversity and ecosystem services in a human-dominated watershed. *Ecological Complexity*, 8(2): 177–183.
- Bangash R F, Passuello A, Sanchez-Canales M *et al.*, 2013. Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. *Science of the Total Environment*, 458: 246–255.
- Baskett E Z, Keles S, Yolasigmaz H A, 2008. Comparing multipurpose forest management with timber management, incorporating timber, carbon and oxygen values: A case study. *Scandinavian Journal of Forest Research*, 23(2): 105–120.
- Bennett E M, Balvanera P, 2007. The future of production systems in a globalized world. *Frontiers in Ecology and the Environment*, 5(4): 191–198.
- Bennett E M, Peterson G D, Gordon L J, 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters*, 12(12): 1394–1404.
- Bhagabati N K, Ricketts T, Sulistyawan T B S *et al.*, 2014. Ecosystem services reinforce Sumatran tiger conservation in land use plans. *Biological Conservation*, 169: 147–156.
- Braat L C, ten Brink P, 2008. The Cost of Policy Inaction (COPI): The case of not meeting the 2010 biodiversity target. Wageningen: Alterra.
- Bradford J B, D'Amato A W, 2012. Recognizing trade-offs in multi-objective land management. *Frontiers in Ecology and the Environment*, 10(4): 210–216.
- China's State Forestry Administration (CSFA), 2014. China's Forest Resources Report, 2009–2013. Beijing: China Forestry Publishing House. (in Chinese)
- Costanza R, d'Arge R, deGroot R *et al.*, 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387(6630): 253–260.
- Daily G C, 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, D.C.: Island Press.
- de Groot R S, Wilson M A, Boumans R M J, 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, 41(3): 393–408.
- Delphin S, Escobedo F J, Abd-Elrahman A *et al.*, 2013. Mapping potential carbon and timber losses from hurricanes using a decision tree and ecosystem services driver model. *Journal of Environmental Management*, 129: 599–607.
- Dixon J A, Scura L F, Vanthof T, 1993. Meeting ecological and economic goals: Marine parks in the Caribbean. *Ambio*, 22(2/3): 117–125.
- Dong Ming, Wang Yifeng, Kong Fanzhi *et al.*, 1997. *Survey, observation and analysis of terrestrial biocommunities*. Beijing: China Standards Press. (in Chinese)
- Fang Jingyun, Yu Guirui, Ren Xiaobo *et al.*, 2015. Carbon sequestration in China's terrestrial ecosystems under climate change: Progress on ecosystem carbon sequestration from the CAS Strategic Priority Research Program. *Bulletin of Chinese Academy of Sciences*, 30(6): 848–857. (in Chinese)
- Feng X M, Fu B J, Piao S L *et al.*, 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, 6(11): 1019–1022.
- Fotakis D G, Sidiropoulos E, Myronidis D *et al.*, 2012. Spatial genetic algorithm for multi-objective forest planning. *Forest Policy and Economics*, 21: 12–19.

- Fu Bojie, Zhou Guoyi, Bai Yongfei *et al.*, 2009. The main terrestrial ecosystem services and ecological security in China. *Advances in Earth Science*, 24(6): 571–576. (in Chinese)
- Li Shuangcheng, Zhang Caiyu, Liu Jinlong *et al.*, 2013. The tradeoffs and synergies of ecosystem services: Research progress, development trend, and themes of geography. *Geographical Research*, 32(8): 1379–1390. (in Chinese)
- Liao Lianglin, Zhou Lei, Wang Shaoqiang *et al.*, 2016. Carbon sequestration potential of biomass carbon pool for new afforestation in China during 2005–2013. *Acta Geographica Sinica*, 71(11): 1939–1947. (in Chinese)
- Millennium Ecosystem Assessment, 2003. *Ecosystems and Human Well-Being: A Framework for Assessment*. Washington, DC: Island Press.
- Ministry of Water Resources of China, Chinese Academy of Sciences, Chinese Academy of Engineering (MWRC-CAS-CAE), 2010. *Water and Soil Conservation and Ecological Security in the Red-soil Hilly Region of South China*. Beijing: Science Press. (in Chinese)
- Nelson E, Mendoza G, Regetz J *et al.*, 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, 7(1): 4–11.
- Ouyang Zhiyun, Wang Xiaoke, Miao Hong, 1999. A primary study on Chinese terrestrial ecosystem services and their ecological-economic values. *Acta Ecologica Sinica*, 19(5): 607–607. (in Chinese)
- Ouyang Zhiyun, Zheng Hua, 2009. Ecological mechanisms of ecosystem service. *Acta Ecologica Sinica*, 29(11): 6183–6188. (in Chinese)
- Pan T, Wu S H, Liu Y J, 2015. Relative contributions of land use and climate change to water supply variations over Yellow River source area in Tibetan Plateau during the past three decades. *PLoS One*, 10(4): 1–19.
- Payn T, Carnus J-M, Freer-Smith P *et al.*, 2015. Changes in planted forests and future global implications. *Forest Ecology and Management*, 352: 57–67.
- Qiu J X, Turner M G, 2013. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. *Proceedings of the National Academy of Sciences of the United States of America*, 110(29): 12149–12154.
- Raudsepp-Hearne C, Peterson G D, Bennett E M, 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, 107(11): 5242–5247.
- Research Institute of Wood Industry, Chinese Academy of Forestry (RIWI-CAF), 1982. *Study on Wood Physical and Mechanical Properties of the Dominant Tree Species in China*. Beijing: China Forestry Publishing House. (in Chinese)
- Richards F J, 1959. A flexible growth function for empirical use. *Journal of Experimental Botany*, 10(29): 290–300.
- Rodríguez J P, Beard T D, Bennett E M *et al.*, 2006. Trade-offs across space, time, and ecosystem services. *Ecology and Society*, 11(1): 28.
- Rong Jiantao, Lei Xiangdong, Zhang Huiru *et al.*, 2012. Forest management planning incorporating values of timber and carbon. *Journal of Northwest Forestry University*, 27(2): 155–162. (in Chinese)
- Sun Honglie, Yu Guirui, Ouyang Zhu *et al.*, 2012. *Chinese Ecosystem Observation and Research Dataset-Forest Ecosystem Volume: Hunan Huitong Station (1960–2006)*. Beijing: China Agricultural Press. (in Chinese)
- Tallis H, Kareiva P, Marvier M *et al.*, 2008. An ecosystem services framework to support both practical conservation and economic development. *Proceedings of the National Academy of Sciences of the United States of America*, 105(28): 9457–9464.
- Vonbertalanffy L, 1957. Quantitative laws in metabolism and growth. *Quarterly Review of Biology*, 32(3): 217–231.
- Wang J T, Peng J, Zhao M Y *et al.*, 2017. Significant trade-off for the impact of Grain-for-Green Programme on ecosystem services in north-western Yunnan, China. *Science of The Total Environment*, 574: 57–64.
- Wang Xiaoming, 2013. *Application of multi-objective spatial forest planning based on FPS-ATLAS [D]*. Changchun: Northeast Forestry University. (in Chinese)
- Zeide B, 1989. Accuracy of equations describing diameter growth. *Canadian Journal of Forest Research*, 19(10): 1283–1286.
- Zheng Du, Yang Qinye, Wu Shaohong *et al.*, 2008. *Study on the Eco-geographical Region System of China*. Beijing: The Commercial Press. (in Chinese)
- Zheng Z M, Fu B J, Feng X M, 2016. GIS-based analysis for hotspot identification of tradeoff between ecosystem services: A case study in Yanhe Basin, China. *Chinese Geographical Science*, 26(4): 466–477.