Rubber Plantation Retiring with Simulation of Market-Priced Ecosystem Services in Xishuangbanna, China

Weiguo Liu (liuweiguo110@gmail.com)
Northwest A&F University https://orcid.org/0000-0001-8176-2522
Jiaqi Zhang
Xishuangbanna Tropical Botanical Garden
Yan Yan
Northwest A&F University
Richard T. Corlett
Xishuangbanna Tropical Botanical Garden
Philip Beckschäfer
University of Gottingen
Liang Song
Xishuangbanna Tropical Botanical Garden

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Rubber Plantation Retiring with Simulation of Market-Priced Ecosystem Services in Xishuangbanna, China

Weiguo Liu[1,2*], Jiaqi Zhang[3], Yan Yan[1,2], Richard T. Corlett[3], Philip Beckschäfer[4], Liang Song[5,6*]

[1] Center for Ecological Forecasting and Global Change, College of Forestry, Northwest Agriculture and Forestry University, Yangling, Shaanxi 712100, China.

[2] Qinling National Forest Ecosystem Research Station, Yangling, Shaanxi 712100, China.

[3] Center for Integrative Conservation, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun 666303, Yunnan, China

[4] University of Göttingen, Chair of Forest Inventory and Remote Sensing, Büsgenweg 5, 37077 Göttingen, Germany

[5] CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun 666303, Yunnan, China

[6] Center of Plant Ecology, Core Botanical Gardens, Chinese Academy of Sciences, Menglun 666303, Yunnan, China

[*] Corresponding Author:

Weiguo Liu, Email: liuweiguo110@nwafu.edu.cn.

Liang Song, Email: songliang@xtbg.ac.cn

Abstract:

Background

Until 50 years ago, Xishuangbanna was a heavy forest-covered region with high biodiversity. Attributed to the rubber boom that took place in the region during the last decades, natural forest area decreased quickly and was replaced by monoculture rubber plantations (*Hevea brasiliensis*). To slow down the deforestation rate and encourage rubber plantation retiring, a market and government-combined compensatory payment system was developed with consideration of market-priced ecosystem services.

Results

In the baseline scenario, the annual retiring rate reduced from 9,353±17.8 ha to 4,669±18.5 ha in the projection period, and the final total retiring area in 2050 was 202.477±0.063 thousand ha. The compensatory payment increased along with the growth of rubber plantations. In the projected period (2021-2050), the total NPV (net present value) of compensatory payment was $3,364.820±1.669 million. The total carbon sequestration benefit resulting from replacement of artificial rainforests was 11.718±0.005 million tC. In sensitivity analyses, more uncertainties of compensatory payment were expected with a higher variation of rubber price. The rise of carbon price, discount rate and traditional medicine price, and the decrease of rubber price and final retiring rate could reduce the total NPV of payment.

Conclusions

The market and government-combined payment system has high possibility to effectively encourage rubber retiring and reduce government payment. By the projection of the market and government-combined payment system, most of the small patches of rubber plantation were disappeared in 2050. The annual retiring area decreased gradually along the projection period. The projected compensatory payment and the area-specific payment increased, while the increment of compensatory payment decreased. The carbon sequestration benefit by rubber plantation retiring was negative in the first decade. All the tested factors (i.e., rubber price, rubber price variation, carbon price, final retiring rate, discount rate, and traditional medicine price) could affect the compensatory payment. Currently, the payment system may not so attractive; however, the situation could change when more market-priced ecosystem services are involved in the system.

Keywords: Xishuangbanna, rubber plantation retiring, compensation, market-priced ecosystem services, carbon sequestration

Introduction

As one of the heaviest forest-covered areas in China, Xishuangbanna faces a tremendous loss of forest cover. Because of the boom of the rubber market, monoculture rubber plantations expanded dramatically in the past two decades, especially the species-rich low land. The forest cover decreased from 71% in 2002 to 52% in 2018, and rubber plantations increased from 11% to 21% (Zhang et al., 2019). The rubber plantations expanded from the valleys onto higher, steeper slopes, even into the protected areas (Chen et al., 2016). Large area of rubber plantations in Xishuangbanna has caused a series of ecological and environmental consequences such as biodiversity loss, carbon emission, water and soil erosion, pesticide pollution (Li et al., 2007; Hu et al., 2008; Tan et al., 2011; Chen et al., 2016, Lan et al., 2017), on the other hand side, rubber plantations provided a major contribution to poverty reduction and the local economic development (Lan et al., 2017).

The environmental problems of unregulated rubber expansion have raised concerns of both the central and local governments. The importance of forest restoration is also agreed by scholars and decision-makers. Many measures have been discussed for the effectiveness of encouraging forest restoration, such as crop price restriction, protected area, restrictive regulation, and credit compensation mechanism. The local government in Xishuangbanna also hopes to promote rainforest restoration by increasing eco-compensation for farmers (Yi, 2012). However, the local government needs to balance the requirement for forest restoration and the mandatory demand of the farmers' wealth. The trade-off restricted the potential performance of the measures (Smajgl et al., 2015). The management of agricultural demand, such as sustainable agriculture and waste reduction, can also be considered as an effective policy (Stevanovic et al., 2017). Bateman et al. (2013) provided an approach to valuate ecosystem services for decision-making. The valuation approach (e.g., for carbon sequestration) could increase the incentive of forest preservation (Alhassan et al., 2019).

Payments for ecosystem services were considered as a pivotal incentive to reduce the area of rubber plantation. In the short term, it was suggested that the ecosystem service-based subsidies can slow down deforestation, especially in the downturn of the rubber market after 2014 (Yi et al., 2014a; Zhang et al., 2015). However, compensation is usually difficult to compete with profit from rubber production and increases the financial pressure of the local government. Based on agent-based simulations, currently proposed payments for ecosystem services that designed in Xishuangbanna may fail to meet the reduction objectives (Smajgl et al. 2015). A market-based solution would be preferred as a sustainable policy (Yi et al., 2014a).

Ecosystem services are the benefits that ecosystems provided to human beings. Some ecosystem services are market-priced and traded in the market, such as carbon sequestration, food, timber (Bateman et al., 2013, Bryan et al., 2018). The high supply of those market-priced ecosystem services could boost the local farmers' income. Therefore, the combination of market-priced ecosystem services and government compensatory payment could be more attractive for rubber plantation retiring. In this study, we developed a market and government-combined payment system with market-priced ecosystem services to encourage rubber plantation retiring and forest restoration. The payment system was used as a schematic approach to project the rubber plantation retiring in the next 30 years in Xishuangbanna, China.

Materials and Methods

Study Area

Xishuangbanna Dai Autonomous Prefecture (21°08'N – 22°36'N, 99°56'N – 101°50'N) is located in Yunnan Province, southwest China (Fig. 1). It is on the borders with Laos and Myanmar. This area is only 0.2% (19,200 km^2) of China territory, and 52% is covered by nature forest (i.e., tropical seasonal rainforest, montane rainforest, and evergreen broad-leaved forest) (Zhang et al., 2019). This region holds high biodiversity with 18% of the plant species, 20% of vertebrate species found in China (Pei, 2010). The elevation ranges from 475 m to 2,428 m a.s.l. The annual temperature for the past four decades is 21.7℃ and the annual precipitation is 1,480 mm (Liu et al. 2014). However, the fast expansion of cash crops, such as rubber (*Hevea brasiliensis*) and tea (*Camellia sinensis*), has diminished the natural forest area dramatically from 71% to 52% and induced a decrease in biodiversity (Zhang et al., 2019).

Insert Fig. 1

Insert Fig. 2

Model Development

To reduce the area of rubber plantation, a combination of market-based ecosystem service and government compensatory payment could be a more sustainable policy to encourage rubber plantation retiring without hurting local landowners' income. Therefore, a market and government-combined payment system is developed. In this system, an artificial rainforest is a primary choice for a retired rubber plantation, although artificial rainforests may encounter potential difficulty in the establishment in harsh conditions, such as high elevation and steep slope. A rubber plantation pixel needs to satisfy three conditions before being qualified for retiring (Fig. 2). The first condition is that a decision of retiring would result in more profit for the landowner. The second condition is the rubber plantations should be on the edge of rubber plantation patches. The third condition is that the rate of retired rubber plantation should be confined by the annual retiring rate.

Because the intensively managed rubber plantation is impossible to restore to nature rainforest, an artificial rainforest been established in Xishuangbanna Tropical Botanical Garden is chosen as the ultimate ecosystem for the retired land. When C_r and ES_a are used to represent the opportunity cost of a rubber plantation retiring and economic benefit of market-priced ecosystem services from an artificial rainforest, the rubber plantation is eligible for retiring if:

$$C_r < ES_a + S \quad (1)$$

where C_r and ES_a are calculated in 25-year discounted net present value (NPV) with discount rate r, and S is the compensatory payment from government and also calculated in NPV (Warren-Thomas et al., 2018):

$$C_r = \sum_{n=25}^{i} \frac{c_i}{(1+r)^i} \qquad (2)$$

$$ES_a = \sum_{n=25}^{i} \frac{es_i}{(1+r)^i} \qquad (3)$$

$$\mathrm{S} = \sum_{n=25}^{i} \frac{s_i}{(1+r)^i} \qquad (4)$$

where c_i is the opportunity cost of the rubber plantation retiring from rubber production, timber, and carbon sequestration in year i, es_i is the economic benefit of market-priced ecosystem services from the artificial rainforest (e.g., carbon sequestration, food, traditional medicine, and clean water) in year i, and s_i is the government compensatory payment in year i; r is the discount rate.

Once the rubber plantation pixel satisfies the first condition, the pixel should be on the edge of the rubber plantations patches. This condition ensures a quick reaction to reduce the high fragmentation of nature forest (Zhang et al. 2019). After the plantation pixel is qualified for retiring, the final decision of retiring rubber plantation is randomly generated based on the binomial possibility. Number 1 indicates retiring and number 0 vise verse. The binomial possibility of retiring in year i (b_i) is determined as follows:

$$b_i = \frac{B}{y} \cdot \frac{N_{total}}{N_{edge}} \qquad (5)$$

where B is the demanded final retiring rate after the projection, and y is the length of projection period; N_{edge} and N_{total} are the pixel number on the edge of rubber plantation patches and the total pixel number of rubber plantation. The final retiring rate is the ratio of total retired rubber plantation in the projection period to the initial area of rubber plantation. The final retiring rate is allocated to each projected year for an evenly retiring in the whole projected period. If $b_i \geq 1$, all the eligible plantations will be retired. The annual retiring rate in year i is defined as the ratio between the retired rubber plantations and the total rubber plantations in year i. The compensatory payment is calculated as follows:

$$s_i = c_i + c_i b_i - es_i \quad (6)$$

Model Simulation and Parameter Setting

The calculations of (a) the opportunity cost of a rubber plantation retiring and (b) the economic benefit of market-priced ecosystem services from an artificial rainforest are based on values from the scientific literature.

Above-Ground Biomass

The aboveground biomass accumulation (tC/ha) of rubber plantations and artificial rainforests was simulated by logistic models based on continuous measurements. Because rubber plantations usually have high production when located under 900 m a.s.l. (Song and Zhang, 2010, Min et al., 2017), and 900 m a.s.l. is the boundary of tropical seasonal rainforest and montane rainforest, we adjusted different parameter settings for forests and plantations distributed below 600 m a.s.l., 600-800 m a.s.l., 800-900m a.s.l., and 900 m a.s.l. (Tang et al., 2003, Min et al., 2017). The belowground biomass was assumed 25% of the aboveground biomass (Warren-Thomas et al., 2018). Carbon sequestration was the difference in biomass accumulation between two consecutive years. The parameterized models are as follows:

$$\mathrm{CarRP}_j(\mathrm{a}) = \frac{\tau_{j1}}{1+\tau_{j2}e^{\tau_{j3}a}} \qquad (7)$$

$$\mathrm{CarARF}_j(\mathrm{a}) = \frac{\rho_{j1}}{1+\rho_{j2}e^{\rho_{j3}a}} \qquad (8)$$

where $\mathrm{CarRP}_j(a)$ and $\mathrm{CarARF}_j(\mathrm{a})$ are the aboveground biomass accumulation (tC/ha) of rubber plantations and artificial rainforest distributed below 600 m a.s.l., 600-800 m a.s.l., 800-900m a.s.l., and 900 m a.s.l. when j is 1, 2, 3, 4 respectively, and a is the stand age. The values of the parameters τ_{j1}, τ_{j2}, τ_{j3}, ρ_{j1}, ρ_{j2}, ρ_{j3} can be found in Table 1.

Insert Table 1

Cost and benefit of a rubber plantation

A rubber plantation will not produce natural rubber until the 8th year after stand establishment, and the rubber yield was modeled according to the stand age through a 25-year rotation cycle. The rubber yield curve was generated from the long-term record of the Dongfeng State Farm (Zhang et al., 2015):

$$\ln({}^{\mathrm{Y(a)}}/_{a}) = -0.02686\mathrm{a}^{1.3} + 5.6911 \qquad (9)$$

where Y(a) is rubber yield (kg/ha/year), and *a* is stand age of the rubber plantation. The yields of different elevation ranges were adjusted as ratios of the yield curve in Eq. 11 based on Min et al. (2017). The ratios were 0.98 for below 600 m a.s.l., 1 for 600-800 m a.s.l., 0.75 for 800-900m a.s.l., and 0.47 for 900 m a.s.l.

The total investment for rubber plantation includes stand establishment cost, management cost and labor cost (Yi et al., 2014a). The establishment cost is the total cost from age 1 to 7 of rubber plantation and was estimated to be \$384/ha/year. The management cost occurs when the tapping begins. The cost was \$1,202/ha/year. The tapping cost was \$2.058, \$2.1, \$1.575 and \$0.987/tree/year for below 600 m a.s.l., 600-800 m a.s.l., 800-900m a.s.l., and 900 m a.s.l. The plantation density was 495 trees/ha.

When the stand age is 25 years old, the plantation will be harvested with a harvest cost of \$9.58 per cubic meter of timber (Yi et al., 2014a). A total of 61% of the aboveground biomass was assumed as timber outputs (Daioglou et al., 2016). Carbon content 47% and wood density 650 kg/m^3 were used to convert mass-based to volume-based biomass (Balsiger et al., 2000).

In this study, the opportunity cost was the sum of economic values from natural rubber, timber and carbon sequestration subtracted by total investment. The timber price was the current market price \$724.6/m^3 from China Timber Price Report (http://www.chinatimber.org/price/). The natural rubber price was the average from 2010 to 2019: \$2.47/kg (FRED, 2020). The carbon price was decided as the average carbon trading price in China: \$11.37/tC by the International Carbon Action Partnership (ICAP, 2019). The opportunity cost was as follows:

$$c_i = rb_i + t_i + csru_i - cec_i - cm_i - cl_i - ch_i - csl_i \qquad (10)$$

where rb_i, t_i and $csru_i$ are the economic values from natural rubber, timber and carbon sequestration in the rubber plantation in year *i*, respectively; cec_i, cm_i and cl_i are establishment cost, management cost, and labor cost in year *i*, respectively; ch_i is the cost from timber harvest, and csl_i is the economic value of carbon storage loss during timber harvest in year *i*.

Cost and benefit of an artificial rainforest

The parameters of the artificial rainforest were based on the demonstrative artificial rainforest in Xishuangbanna Tropical Botanic Garden in Menglun, Xishuangbanna. The stand was established between 1960 and 1970 with dominant species: rubber (*H. brasiliensis*), devil pepper (*Rauvolfia verticillata*) and baccaurea (*Baccaurea ramiflora*). The leaf of devil pepper can be used as traditional medicine and market-priced at \$2.9/kg. The leaf biomass was estimated based on the percentage (3.6%) of annual net primary production in the inventory data (Tang et al., 2003). The optimal fruit yield of baccaurea was assumed 0.5kg/tree after 10 years of growth (430 trees/ha) and market-priced at \$8.8/kg (Luo et al., 2014). The fruit yields for different elevation ranges were adjusted by the same ratios for rubber yields. The labor costs to collect fruit and medicine were \$652/ton and \$326/ton, respectively. The simulation of natural rubber yield was obtained by multiplying a coefficient to the rubber yield curve. The coefficient was 370/495 based on the rubber density. The establishment cost was \$730/ha (including seedling purchasing, transportation and planting). The labor cost of natural rubber harvest was also obtained by multiplying the coefficient 370/495.

The economic benefit from ecosystem service of artificial rainforest was calculated based on natural rubber, fruit, traditional medicine and carbon sequestration subtracted by associated costs:

$$es_i = rbar_i + f_i + tm_i + csar_i - cp_i - crh_i - cfh_i - cmh_i \quad (11)$$

where $rbar_i$, f_i, tm_i and $csar_i$ are economic values from natural rubber harvest, fruit, traditional medicine, and carbon sequestration in the artificial rainforest in year *i*, respectively; $\mathrm{cp_i}$, crh_i, cfh_i and cmh_i are costs of artificial rainforest establishment, natural rubber harvest, fruit collection and traditional medicine collection in year *i*, respectively.

The discount rate (*r*) was set at 8%. The projection period was 30 years from 2021 to 2050. A more detailed description of the models and parameters can be found in Tables 2 and 3.

Insert Table 2

Insert Table 3

Land Use Classification and Stand Age of Rubber Plantation

A 2018 land-use map was used as the land-use pattern in 2020 for our projection. We assumed no land-use change from 2018 to 2020. Land use/land cover data for 2018 was classified by 32 Landsat images which were downloaded from Earth Explorer (http://earthexplorer.usgs.gov/). The nearest-neighbor-object-based phenology approach was applied for the classification (Zhai et al., 2018). Google Earth data were used for training and validation. The overall classification accuracy was 96.2%. Six land use/land cover types were identified: natural forests (> 30% tree cover, including all natural forest types and bamboo), shrublands (< 30% tree cover, including young secondary forest and degraded forest areas), rubber plantations, tea plantations (identified by the clear trails around them), farmlands (including paddy rice, vegetables, sugar cane, and banana plantations), and other land uses (including urban and industrial areas, quarries, roads, water bodies, and barren land) (Zhang et al., 2019).

The year of rubber plantation establishment was extracted from Beckschäfer (2017) who published a map that depicts the year of plantation establishment at annual time steps from1988 to 2015. The map was produced from an analysis of a very dense time series of Landsat TM and ETM+ data. Map validation revealed that the root mean square error of the map is 2.5 years. The ages of all the identified rubber plantations increased by 5 from 2015 to 2020. If the age was over 25, we assumed the rubber stand would be harvested and reestablished at age 25.

Scenarios Definition and Sensitivity Analyses

In the payment system, the payment will be adjusted according to the opportunity cost and economic benefit from market-priced ecosystem services. The system ensures a stable annual retiring rate of the rubber plantations. The parameter setting for the base case was defined in Table 4.

The effects of six parameters were analyzed in this study, including rubber price, rubber price variation, carbon price, final retiring rate, discount rate, and traditional medicine price (Table 4). The highest and lowest rubber prices were set to the highest and lowest price in the last decade ($4.86/kg and $1.56/kg). Rubber price was assumed to follow a normal distribution and allowed to randomly change with high and low derivations. The derivations were the derivation and half derivation of rubber price in the last ten years 2010-2019, respectively; FRED, 2020). The carbon price was set to $0/tC for the lowest possible price, and $75.6/tC for the highest possible price (the highest price from Korea's Emission Trading Scheme, ICAP, 2019). In the base case, an aggressive retiring rate was expected to reduce the area of rubber plantation to the level before 2001 (Zhang et al., 2019). To test the sensitivity, a moderate (30%) and a conservative (10%) retiring rate were set. The discount rate was changed from 1% to 10% in the analysis. The supply of traditional medicine could be overwhelming as more rubber plantations were retired. To test the reducing price effect of traditional medicine, we considered a moderate price ($1.45/kg) and a low price ($0/kg). A thousand runs were conducted for every case.

Insert Table 4

Results

Retiring Dynamic in the Base Case

In the base case, the final retiring rate of rubber plantation was 51.172±0.016%. A total of 202.477±0.063 thousand ha plantations were retired between 2021 and 2050 in contrast to 395,677.9 ha of rubber plantations in 2020. The annual retiring area reduced constantly within the projection period and was halved in 2050 in comparison to 2021 (Table 5). About 21.26% of the initial rubber plantations were retired in the first decade, and 16.73% and 13.17% in the following two decades. The variance from the random selection of retiring is negligible, which was less than 0.5% of the mean.

As the retiring of rubber plantation progressing, the boundary of the rubber plantations gradually retreated from the edge to the center of rubber plantation patches (Fig. 3). As more rubber plantations were retired, the small patches in the west and north were occupied by artificial rainforests. The large patches in the south were also shrunk. The eradication of small patches promoted fragment reduction of rainforests.

Insert Table 5

Insert Fig. 3

Cost and Carbon sequestration

Starting in 2021, the government needs to pay sufficient compensation to encourage rubber plantation retirement. The NPV of compensation was $3,364.820±1.669 million. The annual compensatory payment can be found in Fig. 4. When a rubber plantation was retired, the corresponding compensatory payment was determined. The first year had more payment for artificial rainforest establishment, and the payment will reduce and stay unchanged in the following years. The annual compensatory payment constantly increased with the accumulation of previously retired plantation. However, the annual payment increment reduced from \$37.13±0.09 million in 2021 to \$20.44±0.10 million in 2050.

Insert Fig. 4

Insert Fig. 5

The total carbon sequestration benefit was 11.718±0.005 million tC which was 57.9±0.03 tC/ha. About 75% of the carbon sequestration benefit was contributed by timber harvest occurred in the rubber plantations, and 25% was from the growth of the artificial rainforests. The annual benefit of carbon sequestration from the retirement of rubber plantation to an artificial rainforest was negative in the first decade. The carbon sequestration benefit started to increase after 2027 and peaked in 2037 (Fig. 5). The benefit dropped and increased steadily after the peak.

Sensitivity

The six factors that analyzed in this study prominently affected the government compensatory payment (Table 6). The high rubber price (96.8% higher than the base case) can effectively increase the compensatory payment by 41.2%, and low rubber price (36.8% lower than the base case) reduced payment by 15.7% (Fig. 6a). The randomly generated rubber price could introduce more uncertainty of compensatory payment (Fig. 6b). The high and low rubber price variations resulted in that the deviations were 2.6% and 1.5% of the mean payment (0.50% in the base case). The annual payment diminished along with the increase of carbon price and decrease of the discount rate (Fig. 6c, e). A 5.65 times increase in carbon price brought down the compensatory payment in NPV by 2.1%. The discount rate changed from 10% to 1% could increase total compensatory payment in NPV by 3.5 times. The lower requirement for the final retiring rate could reduce the compensatory payment (Fig. 6d). In contrast to the retiring rate 50%, and NPV of compensatory payment for 30% and 10% retiring rates were reduced by 41.6% and 81.2%. The 50% and 100% reduction of traditional medicine could increase total payment in NPV by 6.8% and 13.5% (Fig. 6f).

When considering retiring area and carbon sequestration benefit, no obvious effect could be found from the six factors except the final retiring rate (Table 6). The retired plantation reduced by 31.9% and 74.1%, and carbon storage reduced by 37.8% and 78.6% for moderate and conservative retiring rates, respectively. In the base case, more plantations were retired at the beginning of the simulation period. The retiring area is 9,353.1 ha in 2021 and reduced gradually to 4,669.1 ha in 2050. The ratio between 2021 and 2050 was 2. This ratio reduced to 1.52 and 1.14 for moderate and conservative retiring rates.

Insert Table 6

Insert Fig. 6

Discussion

Model Justification

The market and government-combined payment system is a simplified model for the "rubber to forest" projection. The retiring intention is stimulated by higher expected income from an artificial rainforest and compensatory payment than opportunity cost from a rubber plantation. If all the local landowners are rational, the retiring rate-derived compensation would be a reasonable estimation for government payment. The stands on the edge of rubber plantations are primarily chosen for retiring. This schematic approach could effectively reduce the fragmentations that formed after the rubber boom (Zhang et al., 2019). An even flow allocation of annual retiring rate was adjusted to avoid a sharp increase of compensatory payment and reduce financial pressure for local government. The artificial rainforest is a suitable target vegetation type for the restoration of a rubber plantation, because it has high carbon storage potential and provides more ecosystem services (Tang et al., 2003). We used market-priced ecosystem services to cut down compensatory payment. Currently, many critical ecosystem services are not market-priced, such as water flow regulation, soil conservation, biodiversity (Bateman et al., 2013). If more ecosystem services can be exchanged in the market in the future, the same retiring rate can be retained with less government payment.

Retiring in Base Case

The projected retiring rate was close to the expected retiring rate. Although a random effect was involved, the variation was negligible. Because the number of pixels is very huge, the simulated annual retiring rate can be close to the expected rate (b_i) (Dubois & Prade, 2012). The annual retiring area was the highest in the first year and reduced smoothly thereafter because of the reduction of the total area of plantation. The retiring scheme effectively reduced fragmentation because most of the small patches were replaced by artificial rainforests.

The area-specific payment increases annually because the discount rate was applied for future payment (Zhang et al., 2015). The even restriction on the annual retiring rate is critical for financial purposes. If all the farmers would like to retire their rubber plantations in the year with the most payment, the local government would not be able to afford the compensation payment (Xie et al., 2016). Moreover, to save compensatory expenses, the most favorable strategy is retiring all lands in the last projected year; however, this strategy will minimize the ecosystem services from rubber plantation retiring. In this study, the production of rubber will be terminated after 37 years of growth, which will bring down the economic benefit in an artificial rainforest from natural rubber. However, other market-priced ecosystem services can compensate for the loss of rubber production. In this simulation, the production of fruit is too conservative. The production could be ten times higher if well managed (Luo et al., 2014).

The carbon sequestration benefit is the difference in carbon sequestration between rubber plantations and artificial rainforests. In the early years of retiring, the carbon sequestration in young artificial rainforests is less than that in rubber plantations; therefore, negative carbon sequestration benefit was obtained in the first projected decade (Tang et al., 2003). Because artificial rainforests have higher carbon storage potential (up to 180 tC/ha) than rubber plantation (≈90 tC/ha), the difference became positive in the late growth of artificial rainforests (Tang et al., 2003; Xi, 2009; Yi et al., 2014b). The peak in 2037 is attributed to the age structure of rubber plantations in Xishuangbanna. There are 40% of rubber plantations established in 1987 and 2012 (Beckschäfer, 2017). Those plantations will be harvested in 2037, and the carbon removal was accounted for as the carbon benefit of retiring in this analysis.

Sensitivity Analyses

Six factors (i.e., rubber price, rubber price variation, carbon price, final retiring rate, discount rate, and traditional medicine price) were studied in the sensitivity analyses. The rubber price is the most sensitive factor among all the product prices, because the payment is defined by the profit difference in rubber production between rubber plantations and artificial rainforests. The higher rubber price causes more compensatory payment (Zhang et al., 2015). The rubber price variation increased the variation of compensatory payment. It could also increase the difficulty for local government to determine compensation.

The increase in carbon price could reduce government payment, because the artificial rainforests had higher carbon sequestration potential than the rubber plantations. In the base case, we used the average carbon exchange price in China; however, the price may be conservative in contrast to emission trading worldwide (ICAP, 2019). The carbon price from Korea Emissions Trading Scheme was used as an upper limit, although some even high carbon prices ($403.37/tC) were proposed (Cramton et al., 2017). However, the carbon price is not necessary too high because a very big change can only cause a small change in compensation as far as it was lower than the timber price.

The reduction of the final retiring rate can effectively reduce compensatory payment by reducing the total retiring area, but has no effect on area-specific cost. As the decrease of the final retiring rate, the drop in the annual retiring area became slower because of a more stable ratio of total plantations to the plantations on the edge. A discount rate is recommended between 0% and 10% for an environment project (Sharp et al., 2016). A high discount rate is required if emphasizing future economic benefits. The high discount rate will have more government payment in the future with lower NPV than a low discount rate. The price of traditional medicine in this study will reduce with high supply. If the price decreases to zero, the decrease in the economic benefit of artificial rainforests could cause high compensatory payment; therefore, more market-priced ecosystem services are necessary to encourage retiring (Bateman et al., 2013).

Limits and Uncertainties

Compensatory payment is recommended by Reducing Emissions from Forest Degradation and Deforestation framework (REDD+). In this study, we estimated the compensatory payment by integrating market-priced ecosystem services. However, the prices of the ecosystem services will not stay unchanged, and the change is difficult to predict (Connor et al., 2015). The unstable prices introduce uncertainty to the projection of compensatory payment.

In the estimation of ecosystem services, the carbon dynamics of rubber plantations and artificial rainforests are critical. We adopted logistic models to estimate carbon dynamics. However, the carbon dynamics will change along different environmental gradients, especially the rubber plantations distributed in steep slopes and at high elevations. The simulation could be improved by applying a process-based model, such as the Forest Vegetation simulator (Dixon, 2002) and Triplex (Peng et al., 2002). Therefore, a process-based model should be introduced and calibrated in the future studies.

Moreover, more market-priced ecosystem services should be involved in the compensatory scheme in the future. In this study, we only have natural rubber, fruit, traditional medicine, and carbon sequestration that are considered to offset the profit from a rubber plantation. In the future, more ecosystem services can be exchanged in the market, such as water flow regulation, open-access recreation and biodiversity (Bateman et al., 2013), which can cause more uncertainty in compensatory payment.

In general, monocultures may have higher yields and lower costs for establishment and maintenance, although the market value of ecosystem services from the artificial rainforest will offset some of the cost of replacing rubber monocultures. A diverse replacement forest (e.g., artificial rainforest) will be very expensive to establish, especially when labor costs are relatively high. It should be noted that the artificial rainforest adopted in this study is just a flexible model for rubber plantation retiring, and an alternative that combines the benefits of high carbon sequestration, high native plant diversity, multi-layer structure, *etc*.

Conclusions

In this study, a market and government-combined compensatory payment system were developed to simulate the retiring dynamics that stimulated by economic benefit. In the base case, the annual retiring area reduced smoothly along the projection period. Most of the small patches were disappeared in 2050 due to the restriction on the edge-first retiring strategy. The projected compensatory payment accumulated annually, while the increment of compensatory payment was decreased and the area-specific payment increased. The carbon sequestration benefit from retiring was negative in the first decade. Many factors can affect the compensatory payment, including rubber price, rubber price variation, carbon price, final retiring rate, discount rate, and traditional medicine price. The variation of rubber price increases the uncertainty of compensatory payment. The rise of carbon price and traditional medicine price, and the decrease of rubber price and final retiring rate can reduce the payment. However, the change of the final retiring rate does not affect area-specific payment. The high discount rate reduces NPV of the payment, but increases the annual compensatory payment.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Weiguo Liu and Liang Song conceived the idea and designed the study. Jiaqi Zhang, Richard T. Corlett and Philip Beckschäfer analyzed the GIS datasets. Weiguo Liu and Yan Yan wrote the necessary codes. Weiguo Liu and Liang Song led the writing of the manuscript with substantial contributions from all co-authors. All authors gave final approval for publication.

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Availability of data and materials

Not applicable

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Table 1. Parameter setting for carbon models and rubber yield models at different elevation ranges.

Parameters	Elevation ranges: m a.s.l.			
	<600	600-800	800-900	>900
τ_{j1}	96.74	98.28	0	65.69
τ_{j2}	13.12	13.12	13.12	17.83
τ_{j3}	-0.21	-0.21	-0.21	-0.14
ρ_{j1}	183.49	186.42	140.61	88.11
ρ_{j2}	48.5	48.5	48.5	48.5
ρ_{j3}	-0.18	-0.18	-0.18	-0.18

623 Table 2. Definitions of Notations and associated calculations or models in this study.

Notation	Definition
a	Stand age
B	The demanded final retiring rate after the projection
b_i	Binomial possibility of retiring in year *i*
C_r	Net present value of opportunity cost of a rubber plantation retiring: $/ha
c_i	Opportunity cost of a rubber plantation retiring in year *i*: $/ha
$\mathrm{CarRP}_j(\mathrm{a})$	Aboveground biomass accumulation in rubber plantation at elevation range *j*: tC/ha
$\mathrm{CarARF}_j(\mathrm{a})$	Aboveground biomass accumulation in an artificial rainforest at elevation range *j*: tC/ha
cec_i	Establishment cost in year *i*: $/ha
cfh_i	Costs of natural fruit collection in year *i*: $/ha
ch_i	Cost from timber harvest in year *i*: $/ha
cl_i	Labor cost in year *i*: $/ha
cm_i	Management cost in year *i*: $/ha
cmh_i	Costs of traditional medicine collection in year *i*: $/ha
cp_i	Costs of artificial rainforest establishment in year *i*: $/ha
crh_i	Costs of natural rubber harvest in artificial rainforest in year *i*: $/ha
$csar_i$	Economic values from carbon sequestration in an artificial rainforest in year *i*: $/ha
csl_i	Economic value of carbon storage loss during timber harvest in year *i*: $/ha

$csru_i$	Economic values from carbon sequestration in a rubber plantation in year i: \$/ha
ES_a	Net present value of economic benefit of market-priced ecosystem services from an artificial forest: \$/ha
es_i	Economic values from ecosystem service of an artificial rainforest in year i: \$/ha
f_i	Economic values from fruit in an artificial rainforest in year i: \$/ha
N_{edge}	The pixel number on the edge of rubber plantation patches
N_{total}	The total pixel number of a rubber plantation.
r	Discount rate: %
rb_i	Economic values from natural rubber in a rubber plantation in year i: \$/ha
$rbar_i$	Economic values from natural rubber in an artificial rainforest in year i: \$/ha
S	Net present value of compensatory payment from government: \$/ha
s_i	Compensatory payment from government in year i: \$/ha
t_i	Economic values from timber in a rubber plantation in year i: \$/ha
tm_i	Economic values from traditional medicine in an artificial rainforest in year i: \$/ha
y	The length of the projection
Y(a)	Rubber yield at age a: kg/ha/year

Table 3. Parameter settings for the analysis.

Definition	Values			
	≤ 600	600-800	800-900	> 900
Belowground biomass	25% of aboveground biomass			
Carbon content: tC/t of dry biomass	0.47			
Carbon price: $/tC	11.37			
Fruit price: $/kg	8.8			
Fruit yield: kg/ha	0.49	0.5	0.38	0.24
Labor cost for fruit collection: $/ton	326			
Labor cost for natural rubber harvest in an artificial rainforest: $/ha	761.5	777	582.8	365.2
Labor cost for natural rubber harvest in a rubber plantation: $/ha	1,018.7	1,039.5	779.6	488.6
Labor cost for traditional medicine collection: $/ton	652			
Percentage of merchantable timber: % of biomass	61			
Rubber price: $/kg	2.47			
Rubber yield in an artificial rainforest: kg/ha/year	$\frac{370}{495}$ ×rubber yield in a rubber plantation			
Timber harvest cost: $/m^3	9.58			

Timber price: $\$/m^3$	724.6
Traditional medicine price: \$/kg	2.9
Traditional medicine production: ton/ha	3.6% of annual net primary production
Wood density of rubber: kg/m^3	650

Table 4. Definition of the base case and sensitivity analyses.

Parameter	Base Case	Sensitivity
Rubber price: $/kg	2.47	High: 4.86 Low: 1.56
Rubber price varation: $/kg	$\sim N(2.47, 0)$	High variability: $\sim N(2.47, 1.12)$, Low variability: $\sim N(2.47, 0.56)$
Carbon price: $/tC	11.37	Low possible price: 0 high possible price: 75.6
Retiring rate in 2050	Aggressive: 50%	Conservative retiring rate: 10% Moderate retiring rate: 30%
Discount rate	8%	1%-10%
Traditional medicine price: $/kg	2.9	Moderate price: 1.45 Low price: 0

Table 5. Annual retiring area (ha) and cumulative percentage from 2021 to 2050.

Year	Annual retiring area (mean±sd): ha	Cumulative percentage (mean±sd): %
2021	9,353.07±16.87	2.364±0.004
2022	9,112.47±22.73	4.667±0.007
2023	8,914.25±17.31	6.920±0.007
2024	8,695.51±16.19	9.117±0.009
2025	8,509.12±19.06	11.268±0.009
2026	8,268.35±18.32	13.358±0.012
2027	8,099.53±22.21	15.405±0.011
2028	7,922.15±21.70	17.407±0.010
2029	7,716.56±35.57	19.357±0.008
2030	7,547.63±15.52	21.264±0.008
2031	7,355.77±13.29	23.123±0.009
2032	7,187.84±11.74	24.940±0.009
2033	7,020.11±15.16	26.714±0.008
2034	6,856.97±22.41	28.447±0.008
2035	6,681.07±12.55	30.136±0.006
2036	6,531.03±25.92	31.786±0.009
2037	6,373.23±20.91	33.397±0.009
2038	6,214.97±19.18	34.968±0.011
2039	6,058.76±19.85	36.499±0.012
2040	5,936.33±10.31	37.999±0.011

2041	5,796.40±11.89	39.464±0.011
2042	5,657.75±16.70	40.894±0.011
2043	5,510.92±7.74	42.287±0.011
2044	5,387.30±23.56	43.648±0.013
2045	5,272.09±15.58	44.981±0.011
2046	5,134.39±17.66	46.278±0.015
2047	5,014.90±14.08	47.546±0.015
2048	4,896.39±19.37	48.783±0.015
2049	4,782.83±16.74	49.992±0.015
2050	4,669.10±17.57	51.172±0.016

Table 6. Effect of factors on rubber plantation retirement.

Factors	Scenarios	Area: thousand ha	Carbon sequestration: million tC	Cost in net present value: million $	Return rate: %
Base case		202.477±0.063	11.718±0.005	3,364.820±1.669	51.172±0.016
Rubber Price	High	202.509±0.064	11.715±0.007	4,750.954±4.175	51.180±0.017
	Low	202.489±0.090	11.717±0.008	2,835.458±2.828	51.175±0.024
Rubber price Variation	High variability	202.500±0.058	11.717±0.010	3,435.708±88.516	51.178±0.015
	Low variability	202.480±0.086	11.716±0.008	3,326.476±50.443	51.173±0.022
Carbon price	Low price	202.540±0.104	11.722±0.007	3,377.769±1.628	51.188±0.026
	High price	202.472±0.064	11.716±0.008	3,295.437±1.405	51.171±0.016
Retiring rate	Moderate rate	137.851±0.124	7.286±0.009	1,964.454±2.066	34.839±0.031
	Conservative rate	52.376±0.030	2.510±0.005	633.649±1.018	13.237±0.008
Traditional medicine price	Moderate price	202.487±0.061	11.716±0.009	3,592.325±1.883	51.175±0.015
	Low price	202.483±0.071	11.717±0.007	3,820.052±1.644	51.174±0.018
Discount rate	1%	202.525±0.067	11.717±0.009	9,141.479±7.142	51.184±0.017
	2%	202.560±0.037	11.712±0.009	7,839.642±2.837	51.193±0.009
	3%	202.534±0.087	11.718±0.008	6,746.994±3.649	51.187±0.022
	4%	202.547±0.079	11.718±0.007	5,825.939±2.891	51.190±0.020
	5%	202.526±0.086	11.718±0.009	5,048411±2.633	51.185±0.022
	6%	202.527±0.076	11.719±0.009	4,392.972±2.661	51.185±0.019
	7%	202.494±0.061	11.716±0.009	3,837.117±2.189	51.176±0.016

9%	202.490±0.067	11.710±0.008	2,962.648±2.177	51.175±0.017
10%	202.519±0.086	11.716±0.008	2,620.744±2.096	51.183±0.022

Figure Captions:

Fig. 1. The location of the study area.

Fig. 2. The framework of the market and government-combined payment system.

Fig. 3. The retiring dynamic in different years: a) 2020, b) 2030, c) 2040, d) 2050.

Fig. 4. Compensatory payment in the projected period.

Fig. 5. Annual carbon sequestration in the base case within the projected period.

Fig. 6. Sensitivity analysis of compensatory payment on a) rubber price, b) variation of rubber price, c) carbon price, d) final retiring rate, e) discount rate, and f) traditional medicine price.

Figures

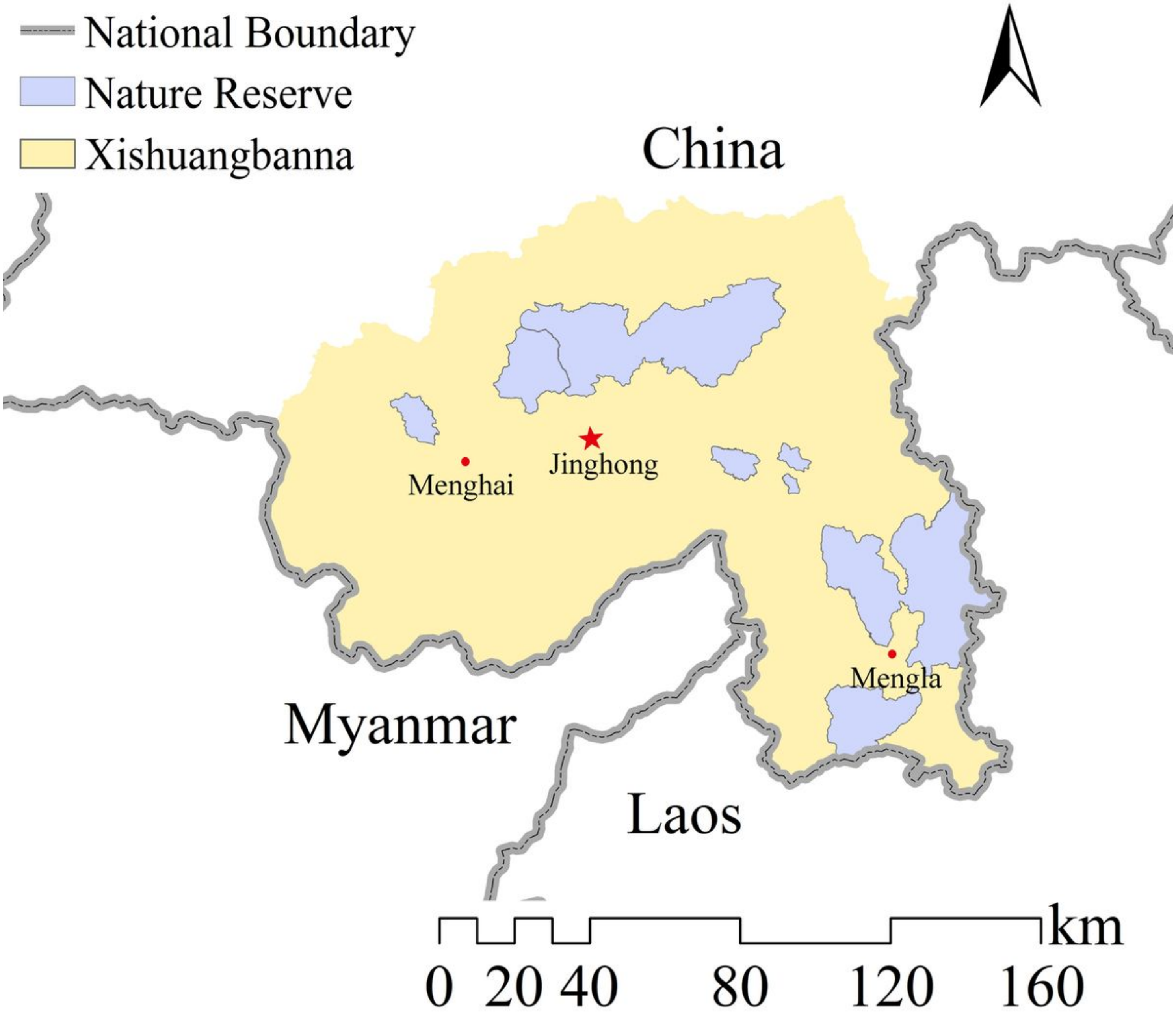

Figure 1

The location of the study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

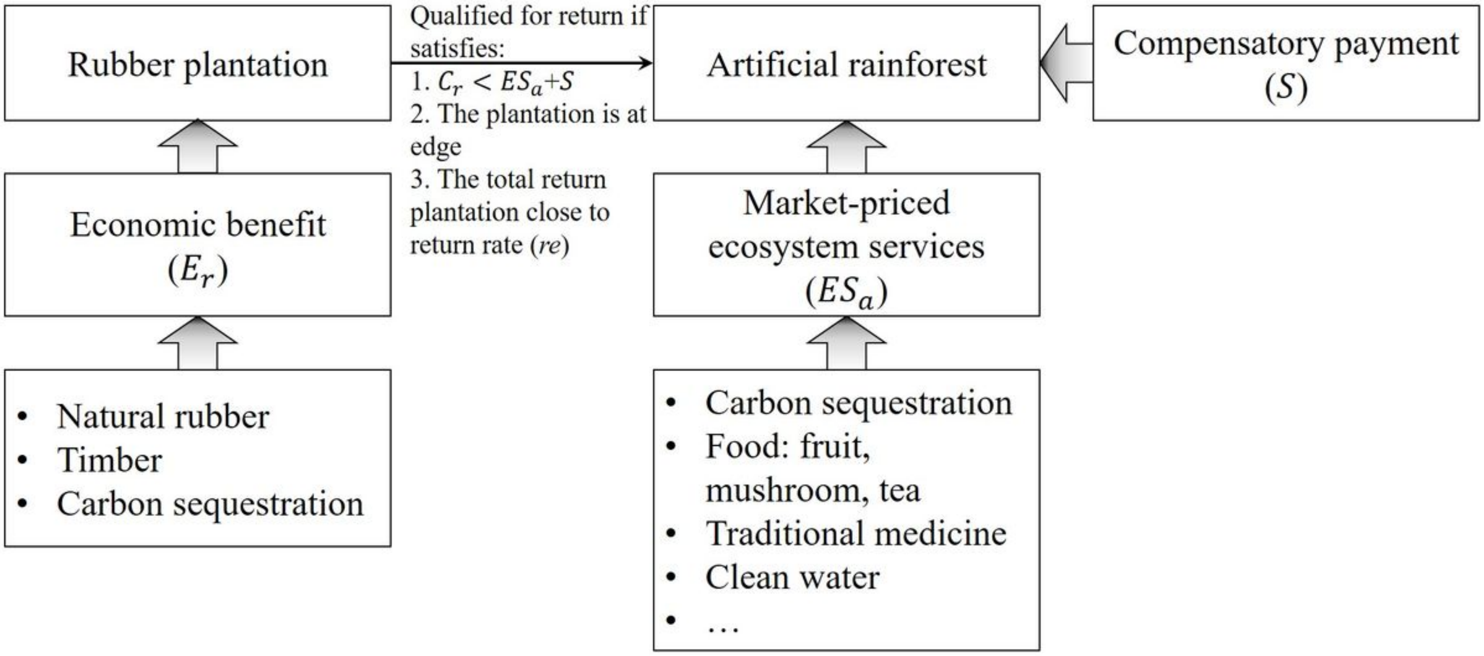

Figure 2

The framework of the market and government-combined payment system.

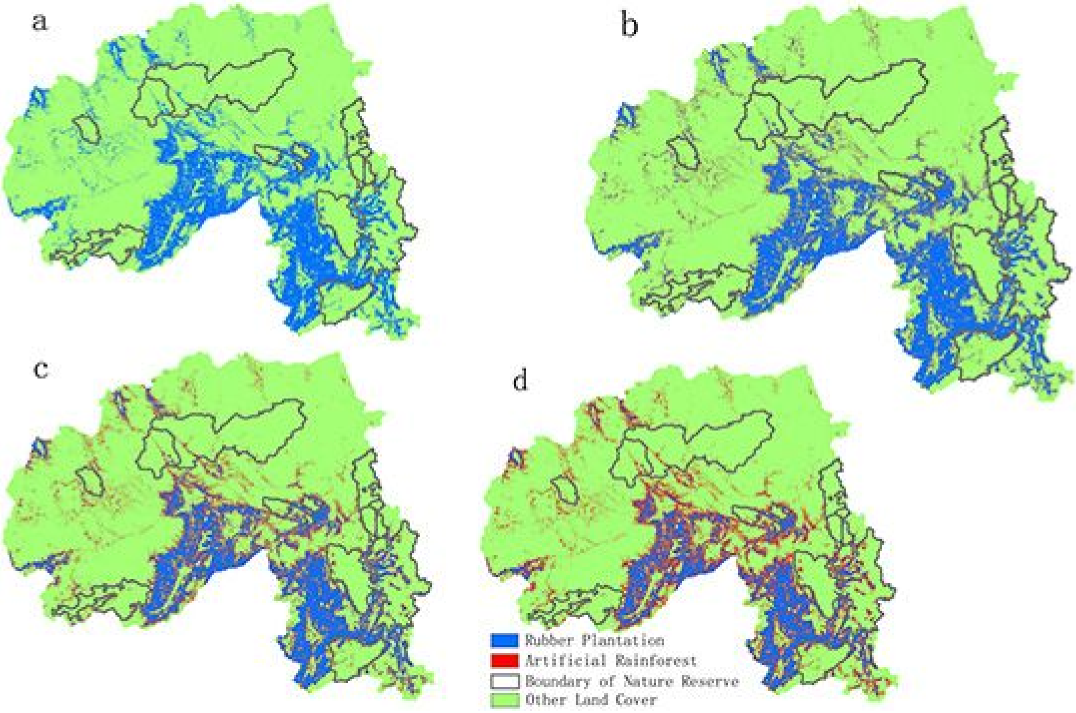

Figure 3

The retiring dynamic in different years: a) 2020, b) 2030, c) 2040, d) 2050. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

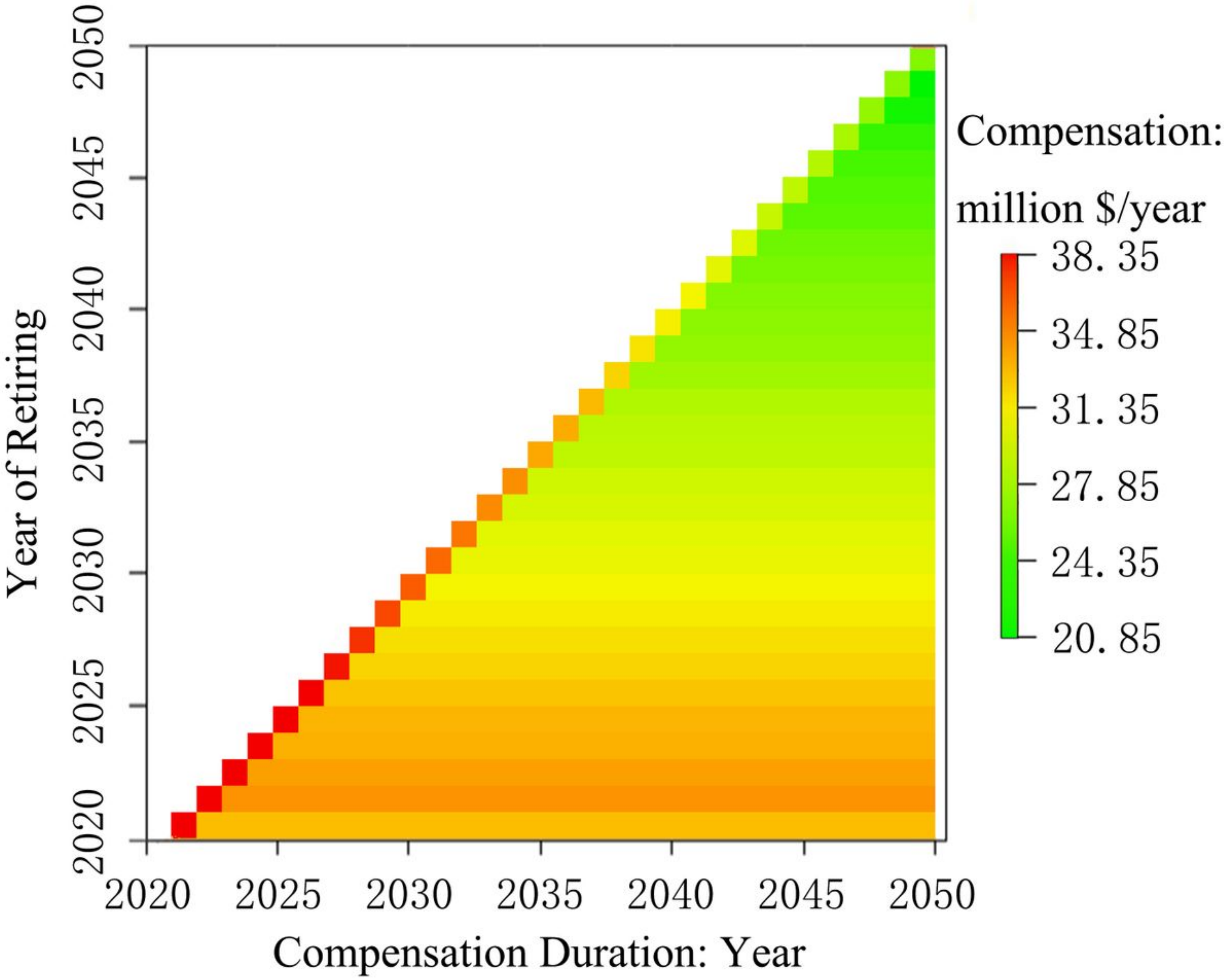

Figure 4

Compensatory payment in the projected period.

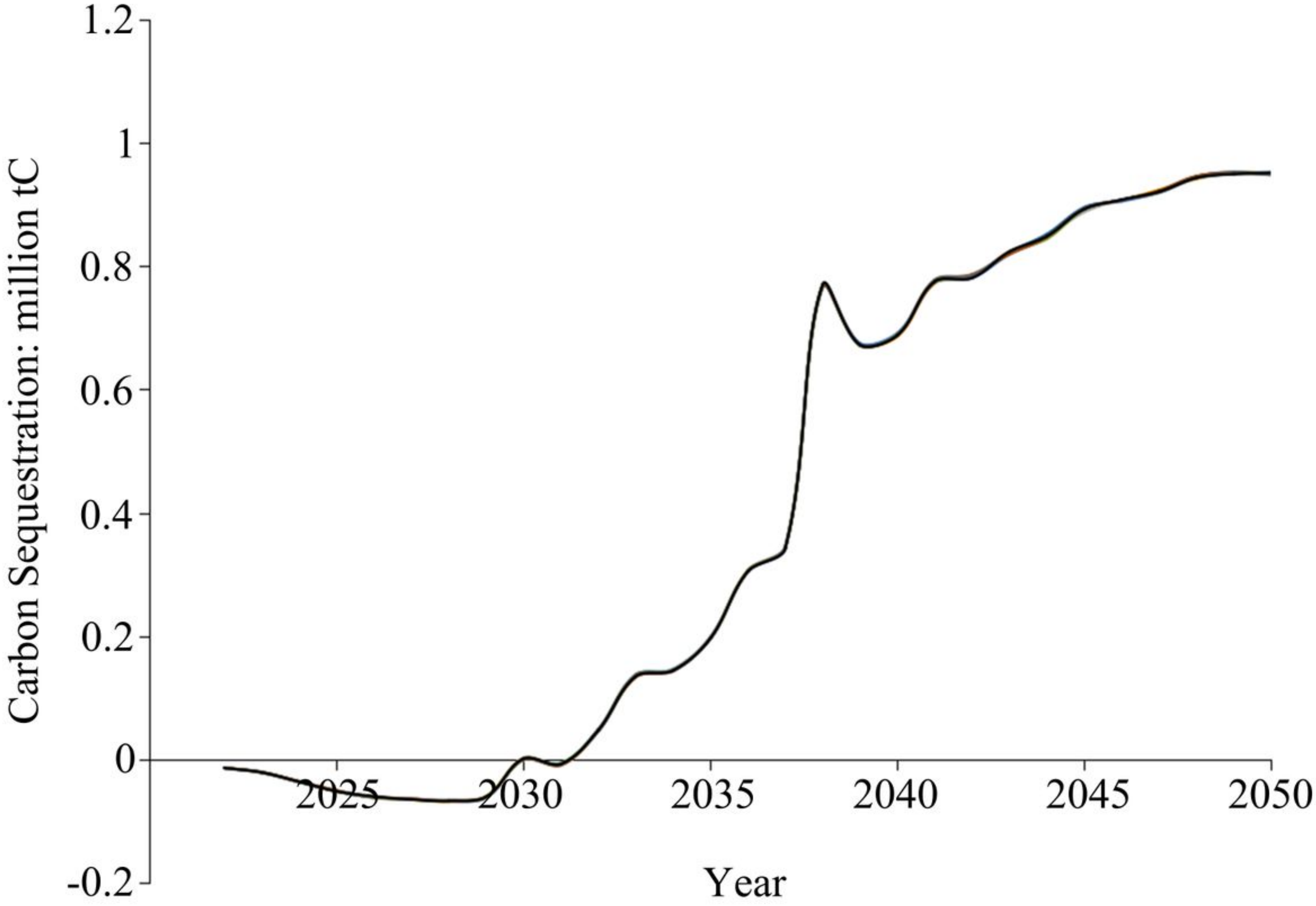

Figure 5

Annual carbon sequestration in the base case within the projected period.

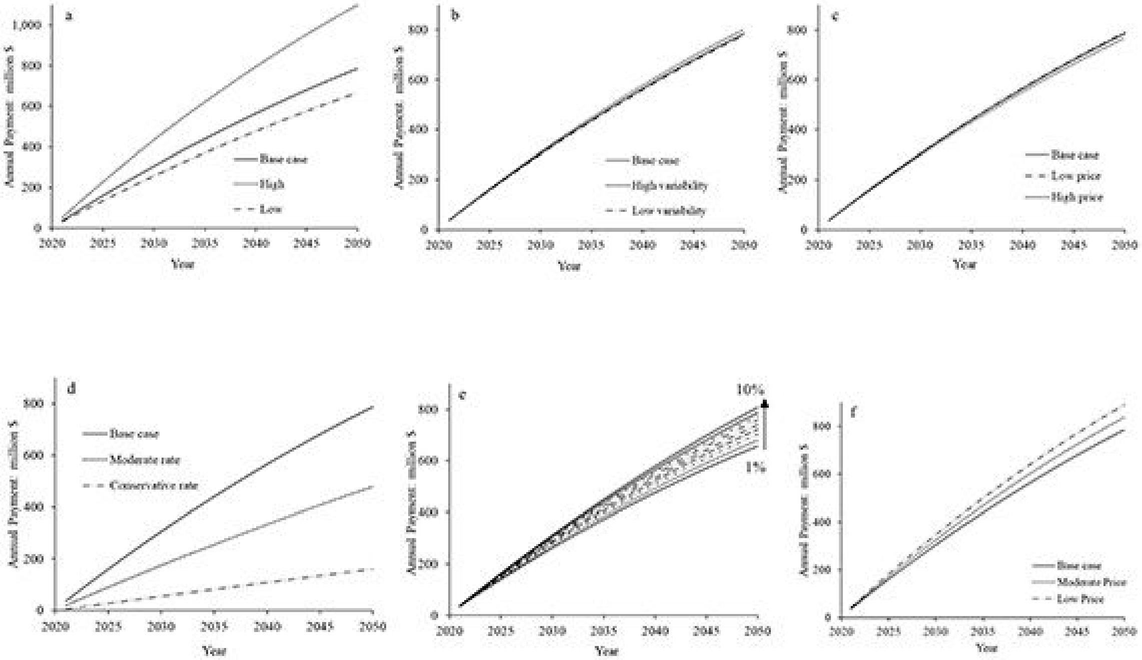

Figure 6

Sensitivity analysis of compensatory payment on a) rubber price, b) variation of rubber price, c) carbon price, d) final retiring rate, e) discount rate, and f) traditional medicine price.