# Encouraging and Advancing the Reconversion of Rubber Plantations: Developing Incentives Using a Combined Market and Government Payment System

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**Research Article**

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# Encouraging and Advancing the Reconversion of Rubber Plantations: Developing Incentives Using a Combined Market and Government Payment System

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**Abstract**: In various regions in Southeast Asia, over the past decades, natural tropical forests have rapidly been converted into monoculture plantations of rubber (*Hevea brasiliensis*), a consequence of the rubber boom. With the goal of slowing the ecologically and environmentally detrimental conversion of forests to rubber plantations and to encourage the reconversion of rubber plantations back to close-to-nature rainforests, we developed a theoretical combined market and government payment system. To evaluate the potential impacts of such system, we carried out a simulation study plus sensitivity analyses, using the latest land-use data from Xishuangbanna, Southwest China. The results of this simulation suggest that the payment system may make the annual reconversion rate develop from 9,009 ha to 4,610 ha over the modeled period from 2021 to 2050, so that the total reconversion area by 2050 would sum up to 197,902 ha. The total net present value (NPV) of compensatory payments for the whole period, in this case, would sum up to US$3.19 billion. The total carbon sequestration benefit resulting from the replacement of rubber plantations would be 11.37 million tons of carbon (tC) over the modelled period, translating into a cost of US$280.44 per tC. Sensitivity analyses revealed that higher variations in rubber prices cause more difficulty in determining compensatory payment. Of course, changes in a number of factors may lead to a reduction of the total NPV of compensatory payments, including increases in the carbon price or traditional medicine price, increases in the discount rate, and decreases to the rubber price and the targeted final reconversion rate. The area-specific compensatory payments ($11,154–$16,106/ha) and area-specific carbon sequestration (46.39–57.45 tC/ha) would then increase linearly as the targeted final reconversion rate increases. This new integrated payment system has the potential to contribute to restoring rainforest in rubber monoculture-dominated landscape.

**Keywords**: Xishuangbanna, rubber plantation reconversion, compensatory payment, market-priced ecosystem services, carbon sequestration, tropical rain forest

## Introduction

Global rubber demand has been rising for decades: more than 52,392 $km^2$ of tropical forests were replaced by rubber (*Hevea brasiliensis*) plantations across mainland Southeast Asia between 2001 and 2014 (Hurni and Fox, 2018). One of the areas formerly most densely dominated by natural forests, Xishuangbanna, which is located in Southwest China and neighbor to Laos and Myanmar, experienced a tremendous forest cover loss, with forest area decreasing from 71% in 2002 to 52% in 2018 (Zhang et al., 2019). Most of these forests were converted to rubber plantations, whose proportion of coverage doubled from 11% to 21% during the same period (Zhang et al., 2019). Starting from the valleys, rubber plantations expanded into marginal lands characterized by higher elevations, steeper slopes, and even encroached into protected areas (Chen et al., 2016; Sarathchandra et al., 2018). While rubber plantations provide a major contribution to poverty reduction and local economic development (Lan et al., 2017), their dramatic spread at the expense of natural forests has caused many unfavorable ecological and environmental consequences, such as loss of biodiversity, increased carbon emissions, pollution of water and landscape by pesticides, and soil erosion (Li et al., 2007; Hu et al., 2008; Tan et al., 2011; Chen et al., 2016; Lan et al., 2017). How to integrate ecological protection into natural rubber latex production systems and how to foster ecosystem services have become key issues in achieving both regional economic growth and sustainable development (Wang et al., 2020).

To date, both scholars and decision-makers have recognized the importance of reconverting rubber plantations back into close-to-nature forests to reconcile the impacts of human development on nature (Warren-Thomas et al., 2018). Various measures have been discussed to foster these reconversion efforts, including the establishment of protected areas, the implementation of restrictive regulations, and the restriction of natural rubber prices (Yi et al., 2014b; Stevanovic et al., 2017; Smajgl et al., 2015). Some studies have suggested that payments for ecosystem services (PES) from the government may promote forest reconversion while reducing deforestation, especially in the downturn of the rubber market after 2011 (Yi et al., 2014a; Zhang et al., 2015). However, PES solely from government can be problematic because they usually fail to outcompete the profit that smallholders expect to gain from rubber production. PES also tend to increase the financial pressure on local governments (Smajgl et al., 2015). Beyond governmental offerings, a market-based solution was also proposed as a potentially successful alternative (Yi et al., 2014a). For instance, some ecosystem services have a market-price and are traded on a regular basis, such as carbon sequestration, and food and timber production (Bateman et al., 2013, Bryan et al., 2018). An economic valuation of market-priced ecosystem services may reveal ways to alleviate the fiscal burden on the government and provide an incentive for both forest preservation and reconversion, especially of the less productive rubber plantations back into forests (Bateman et al., 2013; Alhassan et al., 2019).

In this study, the overall objective is to support the reconversion of rubber plantations into close-to-nature forests so that the ecological services of the landscape are improved. From a technical perspective, the major objectives are (1) to devise a combined market and government payment system, (2) to simulate its implementation in Xishuangbanna, including a prediction of the necessary amount of compensatory payments by the government, and assessing the sensitivities of various factors that may affect the rubber reconversion rate and the required government payments.

## Materials and Methods

The first subsection of this section, “Study Area”, presents background information about Xishuangbanna and the artificial rainforest as the target ecosystem. The second subsection “Land-Use Classification and Stand Age of Rubber Plantation” introduces the methods used to determine the area and age of rubber plantations. In the subsection “Model Development”, we specify the structure of the combined market and government payment system. We then apply the system to Xishuangbanna; models for ecosystem services and opportunity costs can be found in the subsection “Model Simulation and Parameter Setting”. In the last section, we define the baseline and sensitivity analyses.

### *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, and borders of Laos and Myanmar (Fig. 1). Of its area of 19,200 km$^2$, 52% is covered by natural forest, i.e. tropical seasonal rainforest, montane rainforest, and evergreen broad-leaved forest (Zhang et al., 2019). This region is home to a high level of biodiversity, with 18% of the plant species and 20% of vertebrate species found in China (Pei, 2010). The elevation ranges from 475 m to 2,428 m above sea level (a.s.l.). The annual average temperature over the past four decades is 21.7 °C and the annual average precipitation is 1,480 mm (Liu et al., 2014). The fast expansion of cash crops, such as rubber (*H. brasiliensis*) and tea (*Camellia sinensis*) that took place during the last decades reduced natural forest area dramatically and induced a decrease in biodiversity. The area of rubber plantations also doubled while forest patch size decreased 10-fold from 2002 to 2014 (Zhang et al., 2019).

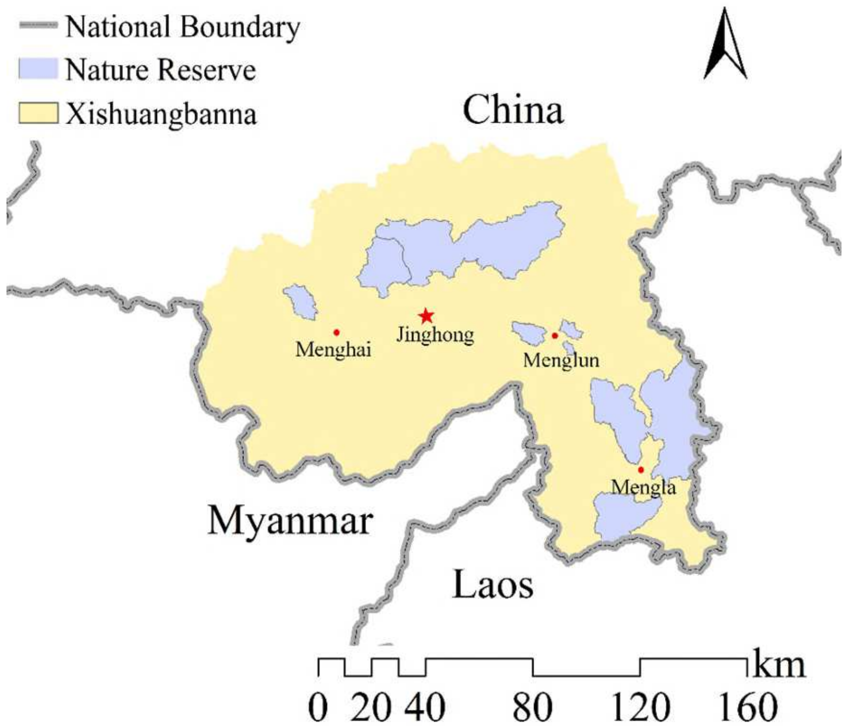


**Fig. 1. The location of Xishuangbanna**

*Target Ecosystem: Artificial Rainforest*

In this paper, we develop a system that aims to set incentives for farmers to convert rubber plantations into artificial rainforests, which are meant to resemble natural rainforests and support the provision of ecosystem services. Considering that an intensively managed rubber plantation cannot be converted into a natural rainforest in the short term, we chose the artificial rainforest as the target ecosystem for the reconverted lands. To assess the benefits resulting from this conversion, we collected data from an experimental site at the Xishuangbanna Tropical Botanical Garden in Menglun, China. The site was created to explore ways to reconvert tropical rainforests from rubber plantations (Tang et al., 2003). An artificial rainforest (1.42 ha) was established on this site in 1960 (see details in the supporting information) in which a permanent observation plot (30 m × 30 m) was set up in 2008 by the Xishuangbanna Tropical Rainforest Ecosystem Station. In total, 48 plant species (40 from the tree layer and 8 from the herbaceous layer) were recorded in the observation plot until 2020 and several studies have shown that, in comparison to rubber plantations, artificial rainforests can support higher levels of biodiversity (Deng et al., 2012), increase carbon sequestration (Tang et al., 2003), improve microclimatic environment (Liu and Duan, 1997), regulate soil temperature (Liu and Li, 1997), and mitigate soil erosion (Deng et al., 2012).

*Land-Use Classification and Stand Age of Rubber Plantation*

A 2018 land-use map by Zhang et al. (2019) depicts Xishuangbanna's land-use pattern in 2018 was used for our projection. We assumed no changes to land-use occurred between 2018 and 2020. The land-use map for 2018 is based on 32 Landsat images that were classified using a nearest-neighbor-object-based phenology approach (Zhai et al., 2018). The overall classification accuracy of the map is 96.2% and it contains six land cover types: 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, 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).

The age of the rubber plantation was a critical piece of information, which we used to simulate rubber yield and correlated ecosystem services provided by the plantation. We used data from Beckschäfer (2017), who mapped the year of plantation establishment during 1988 to 2015 using a very dense time series of Landsat TM and ETM+ data. Map validation revealed the root mean square error of the mapped predictions to be 2.5 years. The ages of all the rubber plantations were increased by 5 to project the map into the year 2020. We assumed the rubber stand has a 25-year rotation length.

*Model Development*

For this paper, we developed a combined market and government payment system (Fig. 2). In this system, farmers that reconvert rubber plantation area into the target ecosystem, an artificial rainforest, receive revenues from payments for market-priced ecosystem services ($ES_a$) and compensatory payments from the government ($S$). The system is based on a raster map in which rubber plantations are represented as pixels (30 m × 30 m in this study). A rubber plantation area (i.e., a pixel) needs to satisfy three conditions before being qualified for receiving compensation payments. The first condition is that the rubber plantation area should be on the edge of a rubber plantation patch. However, the landowners' willingness of reconversion cannot be predetermined. Thus, we assumed that the reconversion decision is a random process and generated by a binomial possibility confined by the targeted final reconversion rate. The second condition is that the decision should be "Yes". Once the second condition is satisfied, the third condition is that this decision to reconvert would result in more profit for the landowner.

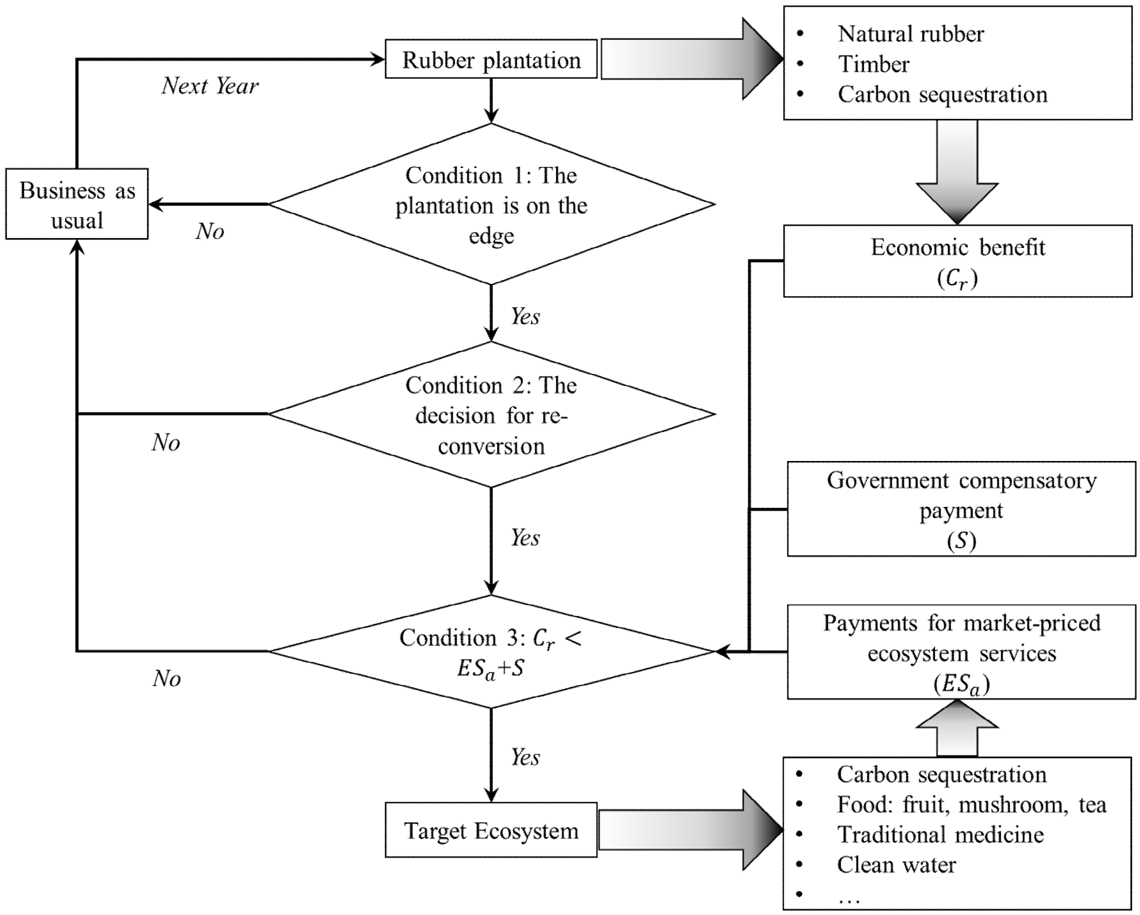


**Fig. 2. The framework of the combined market and government payment system**

The first condition (the edge-first condition) helps remove small rubber plantation patches and, hence, avoid management difficulties from the unnecessary fragmentation of rubber plantations (Zhang et al., 2019). If the plantation is on an edge, the pixel has at least one side adjacent to a different land-use type. After the plantation pixel is confirmed to be on an edge, the decision to reconvert the rubber plantation ("Yes" or "No") is randomly generated based on the binomial possibility $b_i$. The decision is simulated by random generation because all the rubber farms have possibility to reconvert their plantations and the decision is hard to predict. The binomial possibility of reconversion in year *i* is determined as follows:

$$b_i = \frac{B}{m} \cdot \frac{N_{total}}{N_{edge}}, \qquad (1)$$

where $b_i$ is the binomial possibility of reconversion in year $i$ and $B$ is the targeted reconversion rate at the end of the projection. The term $m$ is a number used to enforce an even reconversion and is adjusted in the system to ensure that the final reconversion rate is close to $B$. $N_{edge}$ and $N_{total}$ are the pixel number on the edge of rubber plantation patches and the total pixel number of rubber plantations, respectively. The final reconversion rate is the ratio of total reconverted rubber plantation in the projected period to the initial area of rubber plantation. The annual reconversion rate in year *i* is defined as the ratio between the reconverted rubber plantations and the total rubber plantations in year $i$.

To satisfy the third condition, $C_r$ represents the opportunity cost of a rubber plantation, and $ES_a$ is the economic benefit of market-priced ecosystem services from a target ecosystem. The plantation is eligible for reconversion if:

$$C_r < ES_a + S, \quad (2)$$

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

$$C_r = \sum_{n=25}^{i} \frac{c_i}{(1+r)^i}, \qquad (3)$$

$$ES_a = \sum_{n=25}^{i} \frac{es_i}{(1+r)^i}, \qquad (4)$$

$$\mathrm{S} = \sum_{n=25}^{i} \frac{s_i}{(1+r)^i}, \qquad (5)$$

where $c_i$ is the opportunity cost of the rubber plantation reconversion from rubber production, timber, and carbon sequestration in year *i*, $es_i$ is the economic benefit of market-priced ecosystem services from the target ecosystem in year *i*, and $s_i$ is the government compensatory payment in year *i*; *r* is the discount rate. It is assumed that the incentive of the rubber plantation reconversion will increase with increases in compensatory payments. Therefore, the government compensatory payment is decided as follows:

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

*Model Simulation and Parameter Setting*

To calculate the opportunity cost of a rubber plantation reconversion and the economic benefit of market-priced ecosystem services from an artificial rainforest, the biomass accumulation, carbon sequestration, production of rubber, fruit, timber, and traditional medicine all need to be simulated.

The aboveground biomass accumulation (tC/ha) of rubber plantations and artificial rainforests was simulated using logistic models based on continuous measurements (Tang et al., 2003). The belowground biomass was assumed to be 25% of the aboveground biomass (Warren-Thomas et al., 2018). The rubber yield curve was generated from the long-term record of the Dongfeng State Farm (Zhang et al., 2015). Because rubber plantations usually exhibit a high level of production when located below 800 m a.s.l. (Song and Zhang, 2010, Min et al., 2017), and because 900 m a.s.l. is the accepted boundary between 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 above 900 m a.s.l. (Song and Zhang, 2010, Min et al., 2017). The production of traditional medicines and timber was derived from the aboveground biomass. Fruit yield, as well as the prices of production and costs for establishment and management were empirical values retrieved from previously published papers.

The models and the parameters are specified in detail in the Supporting Information. The projected period was 30 years, set from 2021 to 2050.

*Baseline Definition and Sensitivity Analyses*

In this payment system, the compensatory payments are adjusted according to the opportunity cost and economic benefits derived from the market-priced ecosystem services. The system ensures a stable annual reconversion rate of the rubber plantations. The parameter setting for the baseline is specified in the previous two subsections and is listed in Table 1.

The effects of the six named parameters were analyzed in this study, including rubber price, rubber price variation, carbon price, targeted final reconversion rate, traditional medicine price, and discount rate. 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). The 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 10 years 2010–2019, respectively (FRED, 2020). The carbon price was set to $0/tC for the lowest possible price, and $75.60/tC for the highest possible price (the highest price is from Korea's Emission Trading Scheme, ICAP, 2019). In the baseline, an aggressive reconversion rate was expected to reduce the area of rubber plantations to the level before 2001 (Zhang et al., 2019). To test the sensitivity of the targeted final reconversion rate, reconversion rates were set from 5% to 50% by 5% increments. 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 reconverted. To test the reducing price effect of traditional medicine, we considered a moderate price ($1.45/kg) and a low price ($0/kg). One thousand simulations were conducted for every case.

**Table 1. Definition of the baseline and sensitivity analyses**

| Parameter | Baseline | Sensitivity analyses |
|---|---|---|
| Rubber price ($/kg) | 2.47 | High: 4.86<br>Low: 1.56 |
| Rubber price variation ($/kg) | $\sim N(2.47, 0)$ | High variability: $\sim N(2.47, 1.12)$,<br>Low variability: $\sim N(2.47, 0.56)$ |
| Carbon price ($/tC) | 11.37 | Low possible price: 0<br>high possible price: 75.6 |
| Targeted final reconversion rate in 2050 | Aggressive: 50% | 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50% |
| Traditional medicine price ($/kg) | 2.9 | Moderate price: 1.45<br>Low price: 0 |
| Discount rate (risk-adjusted) | 8% | 1%–10% |

**Table 2. Annual reconversion area (ha) and cumulative percentage from 2021 to 2050**

| Year | Annual reconversion area (ha) | Cumulative percentage (%) | Year | Annual reconversion area (ha) | Cumulative percentage (%) |
|---|---|---|---|---|---|
| 2021 | 9,009.99 | 2.28 | 2036 | 6,411.51 | 30.91 |
| 2022 | 8,859.24 | 4.52 | 2037 | 6,239.16 | 32.49 |
| 2023 | 8,609.04 | 6.69 | 2038 | 6,124.95 | 34.04 |
| 2024 | 8,428.95 | 8.82 | 2039 | 5,964.48 | 35.54 |
| 2025 | 8,220.60 | 10.90 | 2040 | 5,850.09 | 37.02 |
| 2026 | 8,061.93 | 12.94 | 2041 | 5,700.42 | 38.46 |
| 2027 | 7,866.81 | 14.93 | 2042 | 5,571.72 | 39.87 |
| 2028 | 7,703.55 | 16.87 | 2043 | 5,472.99 | 41.25 |
| 2029 | 7,474.50 | 18.76 | 2044 | 5,317.47 | 42.60 |
| 2030 | 7,365.60 | 20.62 | 2045 | 5,167.35 | 43.90 |
| 2031 | 7,194.96 | 22.44 | 2046 | 5,076.72 | 45.19 |
| 2032 | 6,997.50 | 24.21 | 2047 | 4,966.02 | 46.44 |
| 2033 | 6,858.99 | 25.94 | 2048 | 4,795.47 | 47.65 |
| 2034 | 6,689.43 | 27.63 | 2049 | 4,732.56 | 48.85 |
| 2035 | 6,558.93 | 29.29 | 2050 | 4,610.88 | 50.02 |

## Results

### *Reconversion Dynamic in the Baseline*

In the baseline, the final reconversion rate of rubber plantation is 50.02% and a total of 197,901.81 ha of the plantations are reconverted between 2021 and 2050, in contrast to the 395,677.9 ha of rubber plantations in 2020. About 20.62% of the initial rubber plantations are reconverted in the first decade, and 16.4% and 13% in the following two decades (Table 2). The variance from the random selection of reconversion is negligible, which is less than 0.1% of the mean.

As the reconversion of rubber plantations progresses, the boundary of the rubber plantations gradually moves from the edge to the center of rubber plantation patches (Fig. 3). As more rubber plantations are reconverted, the small patches in the west and north are occupied by artificial rainforests. The large patches in the south likewise shrunk.

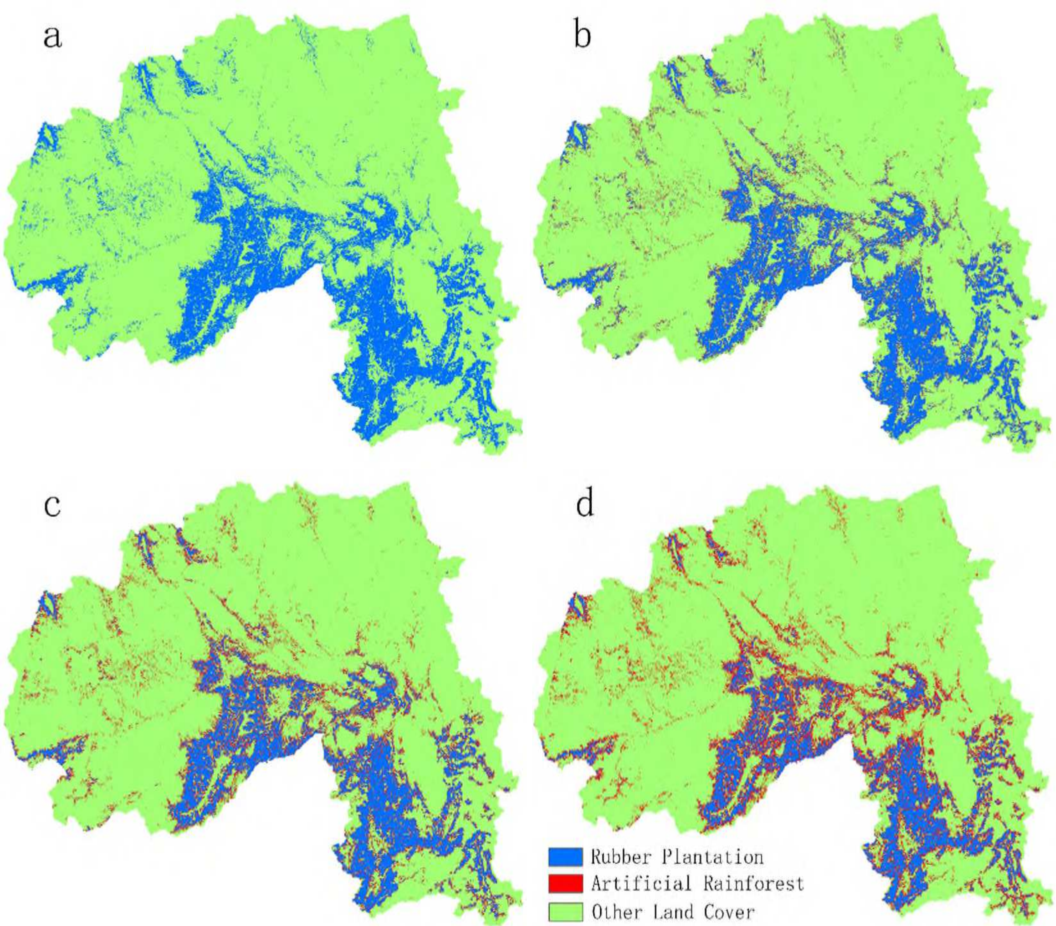


**Fig. 3. The reconversion dynamic through years a) 2020, b) 2030, c) 2040, and d) 2050**

*Cost and Carbon sequestration*

Beginning in 2021, the government needs to sufficiently compensate farmers to encourage rubber plantation reconversion. When a rubber plantation is reconverted, payments to establish artificial rainforests are higher in the first year, and will remain unchanged in the following years (Fig. 4). The overall NPV of compensation amounts to $3.19 billion. The annual compensatory payments constantly increase with the accumulation of previously reconverted plantations. However, the increment of annual payments is reduced over time, from $33.41 million in 2021 to $25.13 million in 2050 (Fig. 4), where the increment of the annual payments is the compensatory payments for the newly reconverted rubber plantations in the specific year.

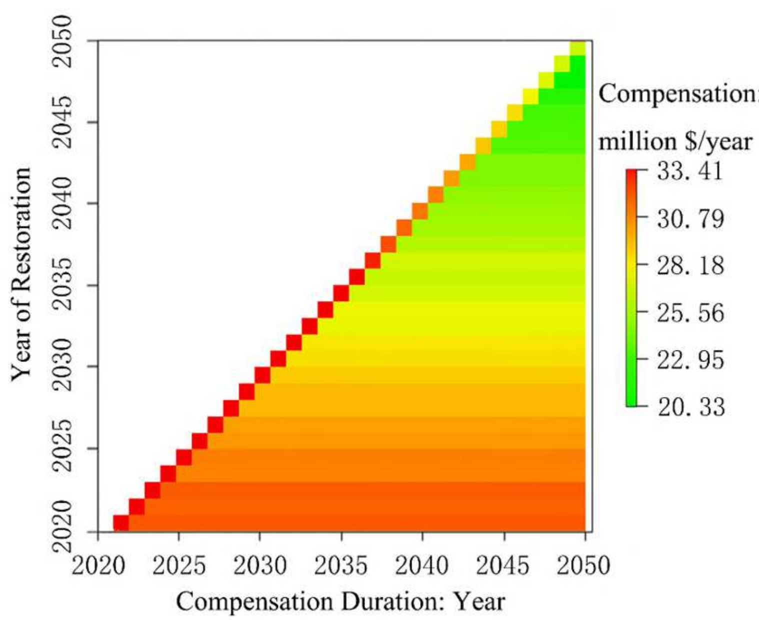


**Fig. 4. Annual compensatory payment increments in the projected period, 2021–2050**

The benefit derived from total carbon sequestration, defined as the difference in carbon sequestration between artificial rainforests and rubber plantations, is 11.37 million tC (57.39 tC/ha). This benefit comes mainly from the growth of artificial rainforests (25%) and the carbon removal (i.e., timber harvest) in old rubber plantations (75%). The annual benefit of carbon sequestration from the reconversion of a rubber plantation to an artificial rainforest is actually predicted to be negative in the first decade, and starts to increase after 2027, with a peak in 2037 (Fig. 5). The benefit drops shortly and increases steadily thereafter.

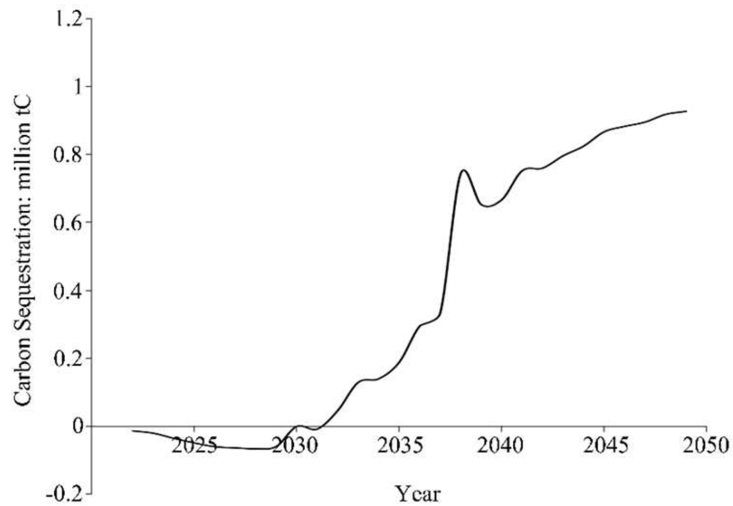


**Fig. 5. Annual carbon sequestration in the baseline within the projected period, 2012–2050**

*Sensitivities*

The six factors in this study pronouncedly affect the government compensatory payments (Table 3, Fig. 6). The annual payments diminish along with the decrease of rubber price, final reconversion rate, discount rate, and the increase of carbon price and traditional medicine price (Fig. 6). The high rubber price (96.8% higher than the baseline) can effectively increase the compensatory payments in NPV by 41.7%, and the low rubber price (36.8% lower than the baseline) reduced payments in NPV by 16.0%. The random variation of rubber price introduces more uncertainty to the compensatory payments. The high and low rubber price variations result in 2.9% and 1.8% deviations of the mean payments (0.1% in the baseline), respectively. A 5.65 times increase in carbon price brings down the compensatory payment in NPV by 2.2%. A change in the discount rate from 10% to 1% can increase total compensatory payments in NPV by 3.5 times. The 50% and 100% reduction of traditional medicine price can increase total payments in NPV by 6.9% and 13.8%, respectively.

A lower requirement for the targeted final reconversion rate reduces the compensatory payment (Table 4). The NPVs of compensatory payments and carbon sequestration increase 14.5 times and 12.4 times from a 5% targeted final reconversion rate to 50%, respectively. The area-specific compensatory payments increase linearly from $11,154/ha for 5% to $16,106/ha for 50%. None of the factors had a significant effect on carbon sequestration except the targeted final reconversion rate. However, a low reconversion rate brings low carbon sequestration benefits.

**Table 3. Effect of the different factors on rubber plantation reconversion**

| Factors | Scenarios | Area: ha | Carbon sequestration (million tC) | Cost in net present value (billion $) | Final reconversion rate (%) |
|---|---|---|---|---|---|
| Baseline | | 197,901.81 | 11.37 | 3.19 | 50.02 |
| Rubber Price | High | 197,744.90 | 11.35 | 4.52 | 49.98 |
| | Low | 197,943.80 | 11.38 | 2.68 | 50.03 |
| Carbon price | Low price | 197,805.42 | 11.37 | 3.2 | 49.99 |
| | High price | 197,752.86 | 11.37 | 3.12 | 49.98 |
| Traditional medicine price | Moderate price | 197,935.92 | 11.37 | 3.41 | 50.02 |
| | Low price | 197,803.08 | 11.37 | 3.63 | 49.99 |
| Discount rate | 1% | 197,839.08 | 11.37 | 8.7 | 50.00 |
| | 2% | 198,021.15 | 11.37 | 7.46 | 50.05 |

| | | | | |
|---|---|---|---|---|
| 3% | 197,905.05 | 11.38 | 6.42 | 50.02 |
| 4% | 197,996.40 | 11.37 | 5.54 | 50.04 |
| 5% | 197,705.79 | 11.35 | 4.78 | 49.97 |
| 6% | 197,722.89 | 11.36 | 4.16 | 49.97 |
| 7% | 197,739.18 | 11.35 | 3.63 | 49.97 |
| 9% | 197,996.94 | 11.38 | 2.81 | 50.04 |
| 10% | 197,889.21 | 11.37 | 2.48 | 50.01 |

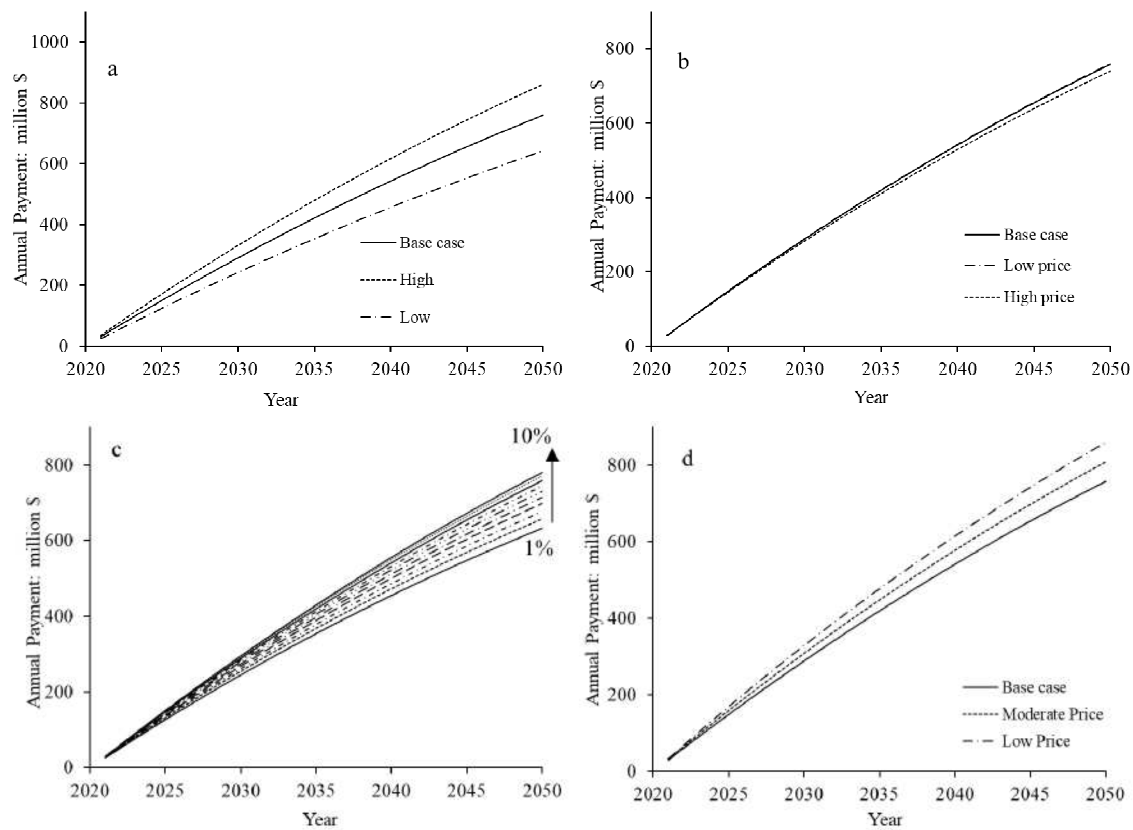


**Fig. 6. Sensitivity analyses of compensatory payments on a) rubber price, b) carbon price, c) discount rate and d) traditional medicine price**

**Table 4. Simulations for different targeted final reconversion rate**

| Targeted final reconversion rate | Area: ha | Carbon sequestration: million tC | Area-specific carbon sequestration: tC/ha | Cost in net present value: billion $ | Area-specific compensatory payment in NPV: $/ha |
|---|---|---|---|---|---|
| 5% | 19,831.95 | 0.92 | 46.39 | 0.22 | 11,154 |
| 10.0% | 39,549.51 | 1.87 | 47.28 | 0.46 | 11,552 |
| 15.0% | 59,317.83 | 2.86 | 48.21 | 0.71 | 11,979 |
| 20.0% | 79,147.89 | 3.9 | 49.27 | 0.98 | 12,371 |
| 25.0% | 98,945.64 | 4.99 | 50.43 | 1.28 | 12,906 |
| 30.0% | 118,639.26 | 6.14 | 51.75 | 1.59 | 13,433 |
| 35.0% | 138,607.74 | 7.34 | 52.96 | 1.94 | 13,996 |
| 40.0% | 158,338.80 | 8.61 | 54.38 | 2.32 | 14,621 |
| 45.0% | 178,027.56 | 9.94 | 55.83 | 2.73 | 15,321 |
| 50.0% | 197,901.81 | 11.37 | 57.45 | 3.19 | 16,106 |

## Discussion

Payments for ecosystem services (PES) had been considered as a panacea for achieving conservation goals, although some people doubted its feasibility and effectiveness as PES would no doubt increase the fiscal expenditure of the government (Smajgl et al., 2015). The combined market and government payment system adopted in this study, however, splits PES into (1) the economic benefit that rubber farmer earn from market-priced ecosystem services and (2) compensation payments from the government. This combination of payments will effectively discourage local farmers from converting the newly established forests back into rubber plantations and relieve the financial burden of local government.

*Reconversion dynamics*

According to the results predicted by the model, the projected reconversion rate is close to the expected reconversion rate. Although a random effect was involved, the variation is negligible, suggesting that the huge number of pixels ensures a simulated annual reconversion rate close to the expected rate ($b_i$) (Dubois and Prade, 2012). The annual reconversion area is the highest in the first year and reduces smoothly thereafter due to the constant temporal reduction of rubber plantations (i.e. an even-flow allocation of the annual reconversion rate), avoiding a sharp increase in compensatory payments and reduce financial pressures exerted on local government (Xie et al., 2016). The annual area-specific payments, on the contrary, increase annually because the positive discount rate is applied for future payments (Zhang et al., 2015).

It should be noted that the production of rubber is assumed to be terminated after 37 years of growth (Yi et al., 2014a), which bring down the economic benefit from rubber growing in the artificial rainforest. However, other market-priced ecosystem services can compensate for the decline of rubber production. It's also worth mentioning that rubber plantations at high altitudes (> 900 m a.s.l.) were established during the rubber boom (2002–2014) in Xishuangbanna and mostly in small patches or on the edge of big patches. Our schematic approach that reconverting the edge stands primarily could remove the small patches and low productivity plantations over time (Zhang et al., 2019), thus improved the connectivity of habitat effectively.

The carbon sequestration benefit is the difference in carbon sequestration between rubber plantations and artificial rainforests. At the beginning of reconversion, a young artificial rainforest will sequester less carbon than an established rubber plantation; therefore, we observe an initial negative carbon sequestration benefit (Tang et al., 2003). However, because artificial rainforests have a higher carbon storage potential (up to 180 tC/ha) than rubber plantations (≈90 tC/ha), the difference is expected to become positive later in the growth of the artificial rainforests (Tang et al., 2003; Xi, 2009; Yi et al., 2014b). We attribute the peak of carbon sequestration benefit in 2037 to the age structure of rubber plantations in Xishuangbanna, 40% of which were established between 1987 and 2012 (Beckschäfer, 2017). Those plantations will be clear-cut in 2037, and in this analysis, the carbon removal is accounted for as the carbon benefit of reconversion.

*Sensitivity Analyses*

Six factors (i.e., rubber price, rubber price variation, carbon price, traditional medicine price, discount rate, and targeted final reconversion rate) were studied in the sensitivity analyses. The rubber price was the most sensitive factor among all the prices of the products because the payments are mainly determined by the profit difference in rubber production between rubber plantations and artificial rainforests. Higher rubber prices give cause to a need for more compensatory payments (Zhang et al., 2015). Variations in the rubber price increase the variation in the compensatory payments, thereby also increasing the difficulty for local governments to determine the appropriate level of compensation.

To analyze the effect of the carbon price, the price from the Korea Emissions Trading Scheme was used as an upper limit, although some higher carbon prices ($403.37/tC) were proposed (Cramton et al., 2017). The increase in carbon price can reduce government payments because the artificial rainforests have higher carbon sequestration potential than the rubber plantations. The traditional medicine price in this study will reduce with a high supply of traditional medicine. If the price decreases to zero, the related decreases in economic benefit from the artificial rainforests could bring about a need for higher compensatory payments from the government.

A discount rate between 0% and 10% was recommended for an environmental project (Sharp et al., 2016). A high discount rate will lead to a low NPV and a need for more government payments in the future as compared with a low discount rate. In this study, to reduce complexity in the calculation, the valuation of carbon sequestration shared the same discount rate as the other merchandise in this study. Many scholars have argued that the discount rate of carbon sequestration should be low to 1.4%, because the investment for carbon sequestration could reduce the risk of investment for the future (Stern, 2007). The low discount rate of carbon sequestration can reduce compensatory payments due to the high carbon sequestration capacity of artificial rainforests.

Changes to the targeted final reconversion rate, which we investigated from 5% to 50%, can increase both the NPVs of compensatory payments and the total benefits of carbon sequestration by encouraging more reconversion of rubber plantations. The final reconversion rate can also affect area-specific payment and carbon sequestration. More area-specific payments and benefits of carbon sequestration occur in higher targeted final reconversion rate scenarios due to more rubber plantations in lower land should be reconverted. As the targeted final reconversion rate decreases, the decline in the annual reconversion area along projected period slowed due to a more stable ratio of total plantations to edge plantation area.

*Limits and Uncertainties*

Compensatory payments are recommended by the Reducing Emissions from Forest Degradation and Deforestation framework (REDD+). In this study, we estimated the compensatory payments by integrating market-priced ecosystem services. The system could potentially be used as a schematic approach of tropical cropland reconversion worldwide, such as for rubber plantations, oil palms, coffee, and cocoa production. However, the prices of the ecosystem services will fluctuate, and these changes are hardly predictable (Connor et al., 2015). Unstable prices introduce uncertainty to the projection of any compensatory payment scheme.

We adopted logistic models to estimate carbon dynamics since the carbon sequestration of rubber plantations and artificial rainforests is a critical ecosystem service. The simulation could be improved by applying a process-based model, such as the Forest Vegetation Simulator (Dixon, 2002) or TRIPLEX (Peng et al., 2002). Therefore, a process-based model should be introduced and calibrated in future studies. Additionally, we only included *H. brasiliensis*, *R. verticillata*, and *B. ramiflora* in the model because they are the three main species in the artificial rainforest in which the most carbon is held (98% biomass and 95% NPP) (Tang et al., 2003). Currently, it is impossible to include other species (mostly grass and shrub) in the model because we do not have similarly detailed information, although these species also contribute to ecosystem services.

Moreover, more market-priced ecosystem services should be involved in the compensatory scheme in the future. In this study, we only considered natural rubber, fruit, traditional medicine, and carbon sequestration 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, soil conservation, open-access recreation, and biodiversity (Bateman et al., 2013), which can reduce the need for higher compensatory payments. By reconverting rubber plantations to artificial rainforests, local farmers may have more free time and can therefore increase their income in the labor market. Therefore, it may be possible to reduce the government payment to a more appropriate level after considering the local farmers' extra income in the future.

In general, monocultures can be characterized as having higher yields and lower costs to establish and maintain. However, the market value of ecosystem services that can be derived from an artificial rainforest is expected to offset some of their relatively higher cost after replacing existing rubber monocultures. It should be noted that the artificial rainforest adopted in this study represents a flexible and simplified model for rubber plantation reconversion, and an alternative that combines the benefits of high carbon sequestration, high native plant diversity, multilayer structure, among other economic and environmental benefits.

## Conclusions

In this study, a combined market and government payment system was developed to simulate the reconversion dynamics of forested rubber plantation as stimulated by economic benefits. In the baseline simulation, the annual reconversion area reduced smoothly along the projected period. Most of the small patches disappeared by 2050 due to restrictions of the edge-first reconversion strategy. The projected compensatory payments accumulate annually, while the incremental compensatory payments decrease. In the first decade, the carbon sequestration benefit from reconversion is negative, but becomes positive in the following decades. Many factors can affect the compensatory payment, including the rubber price, variations in the rubber price, the carbon price, the targeted final reconversion rate, discount rate, and the traditional medicine price. Variations in the rubber price, however, increase the uncertainty of the compensatory payment. Rising carbon price and traditional medicine price, and decreasing the rubber price and the final reconversion rate can lead to reduced payments. A high discount rate also reduces the NPV of these payments, though it would lead to increases in the annual compensatory payment. The approach suggest in this study is likely transferable to other tropical croplands if one aims to reconvert these lands.

## 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 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. Christoph Kleinn, Gbadamassi G.O. Dossa provided innovative suggestions to improve the payment system and this manuscript. Jianjun Huai ensured the necessary corrections on the economic aspect. All authors gave final approval for publication.

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*Availability of data and materials*

Not applicable

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Table 1. Definition of the baseline and sensitivity analyses

Table 2. Annual reconversion area (ha) and cumulative percentage from 2021 to 2050

Table 3. Effect of the different factors on rubber plantation reconversion

Table 4. Simulations for different targeted final reconversion rate

**Figure Captions:**

Fig. 1. The location of Xishuangbanna

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

Fig. 3. The reconversion dynamic in years a) 2020, b) 2030, c) 2040, and d) 2050

Fig. 4. Annual compensatory payment increments in the projected period, 2021–2050

Fig. 5. Annual carbon sequestration in the baseline within the projected period, 2012–2050

Fig. 6. Sensitivity analyses of compensatory payments on a) rubber price, b) carbon price, c) discount rate and d) traditional medicine price

# Figures

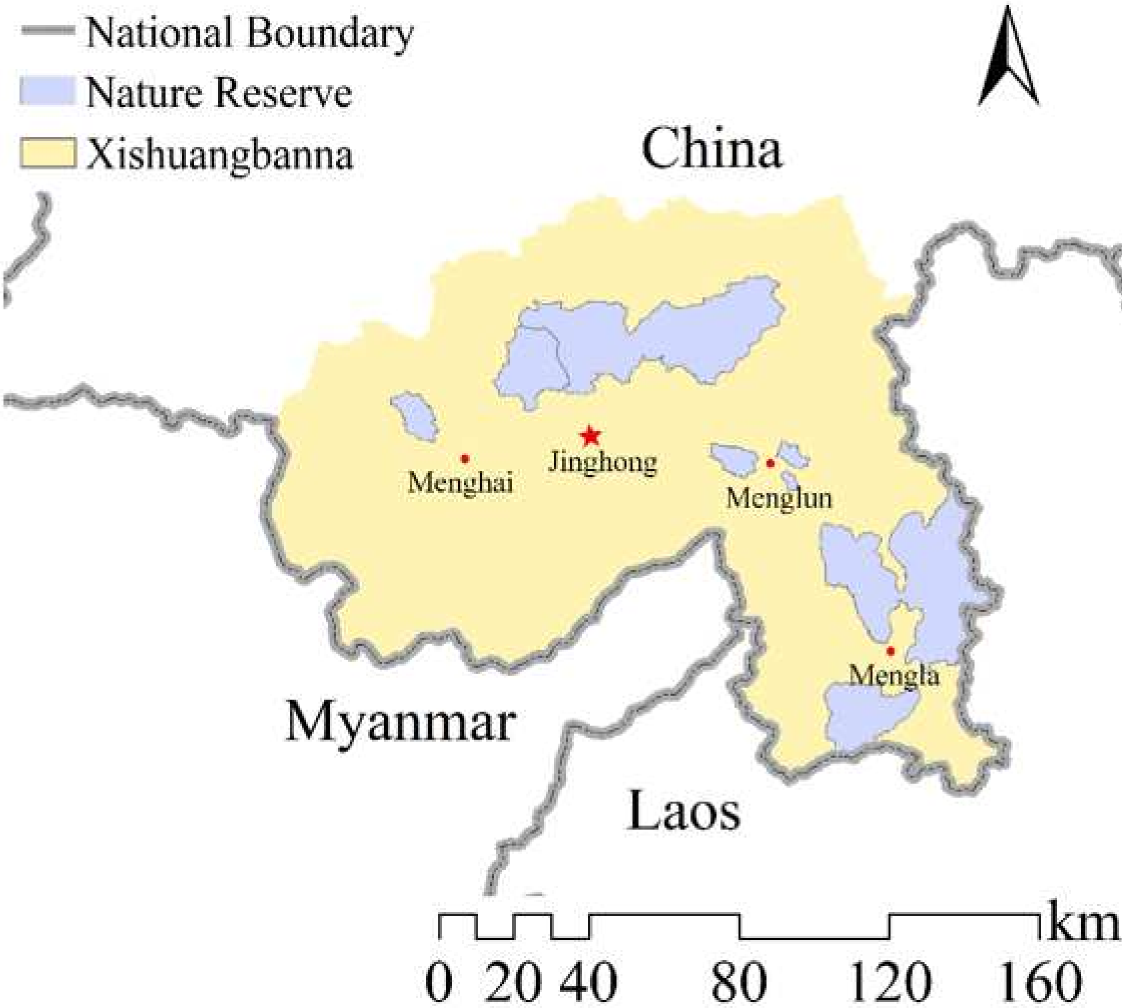



**Figure 1**

The location of Xishuangbanna 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.

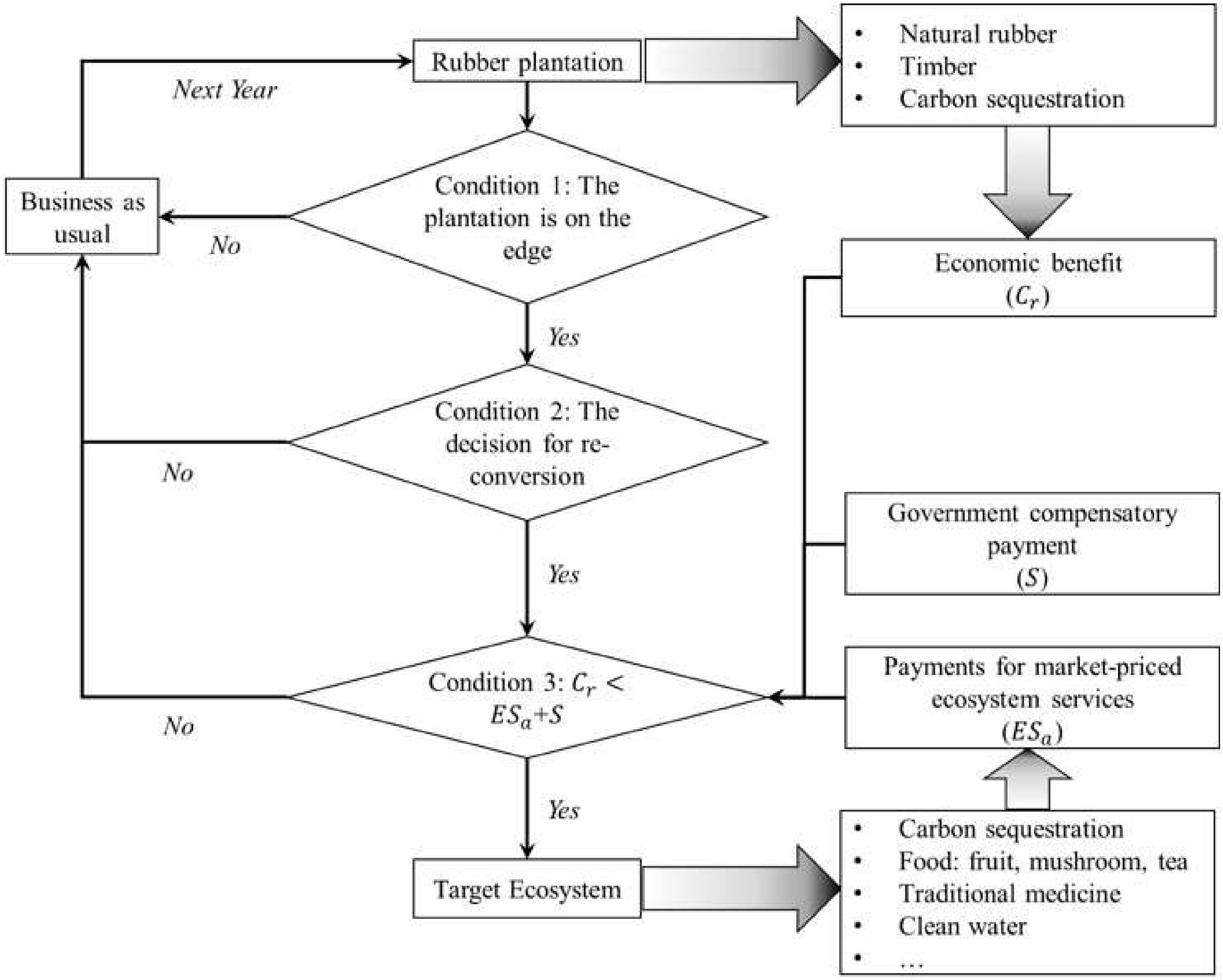
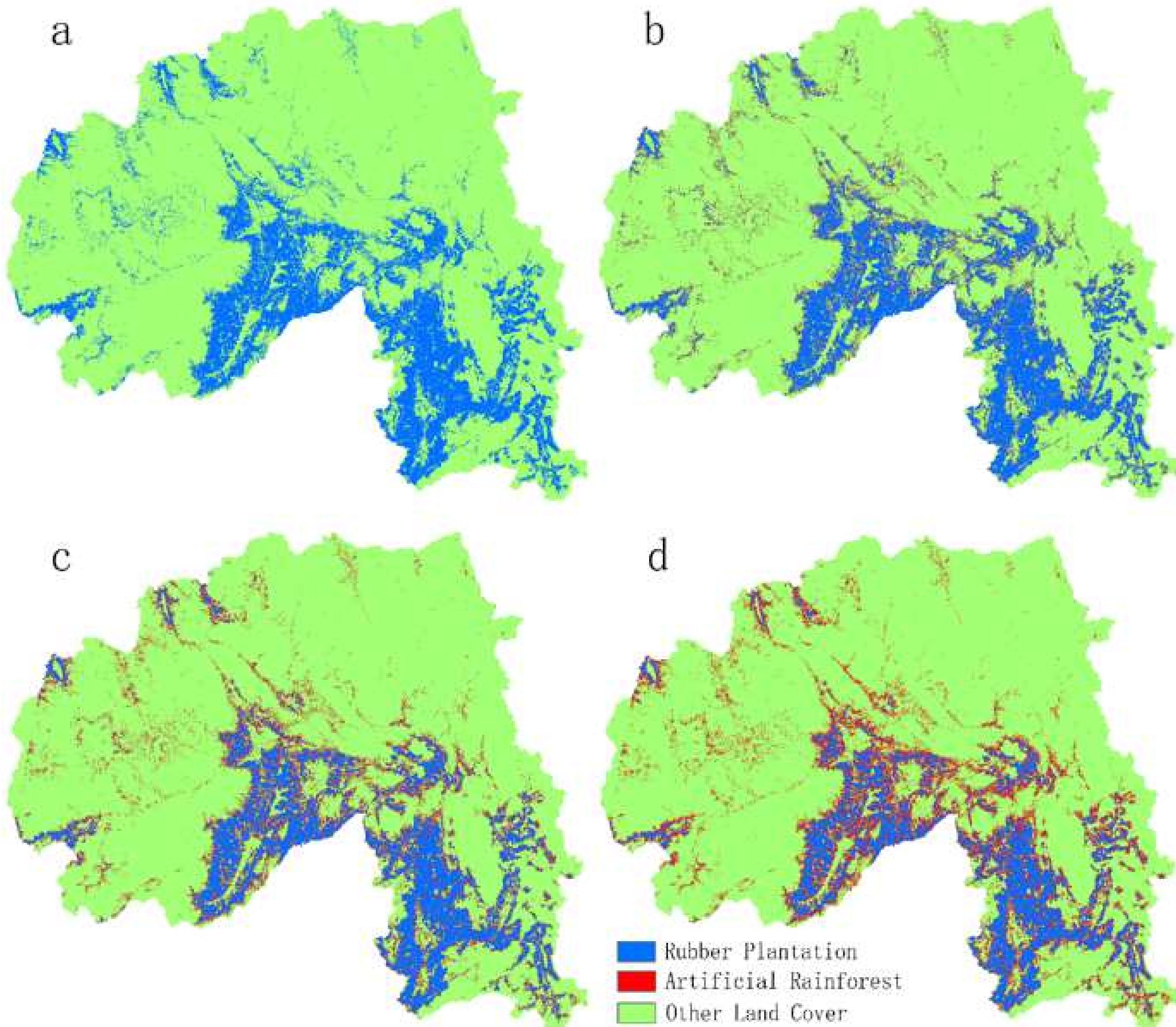



**Figure 2**

The framework of the combined market and government payment system




## Figure 3

The reconversion dynamic in years a) 2020, b) 2030, c) 2040, and 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.

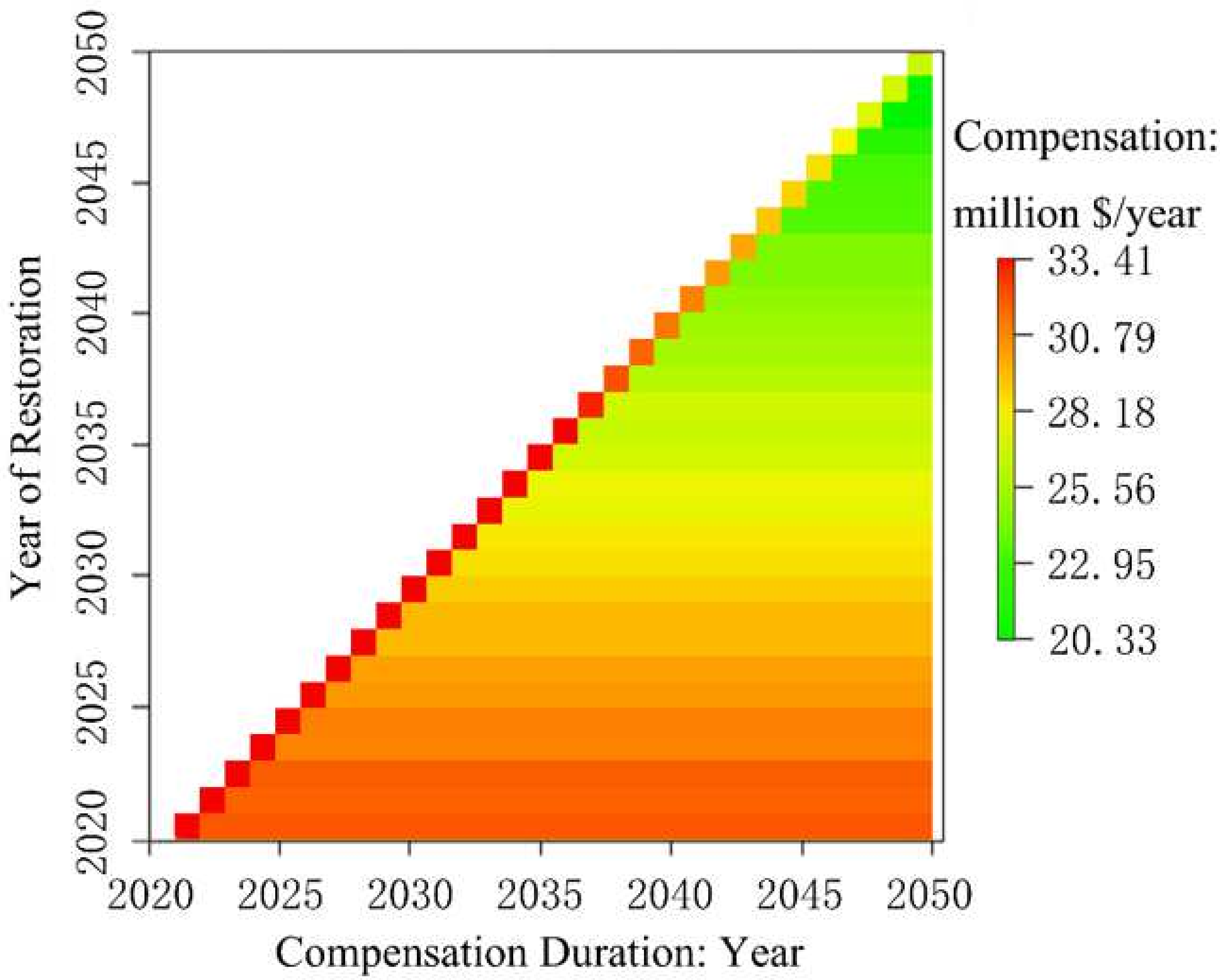



Figure 4

Annual compensatory payment increments in the projected period, 2021–2050

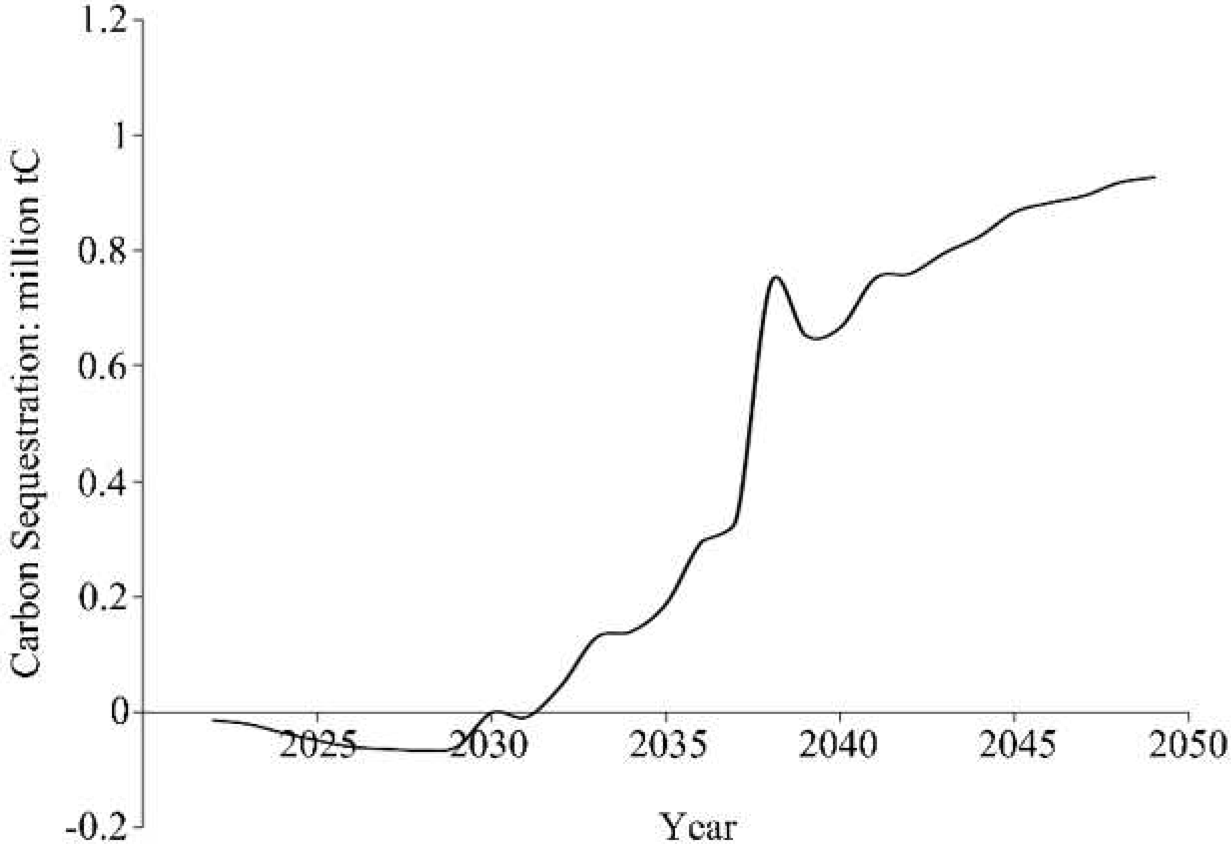
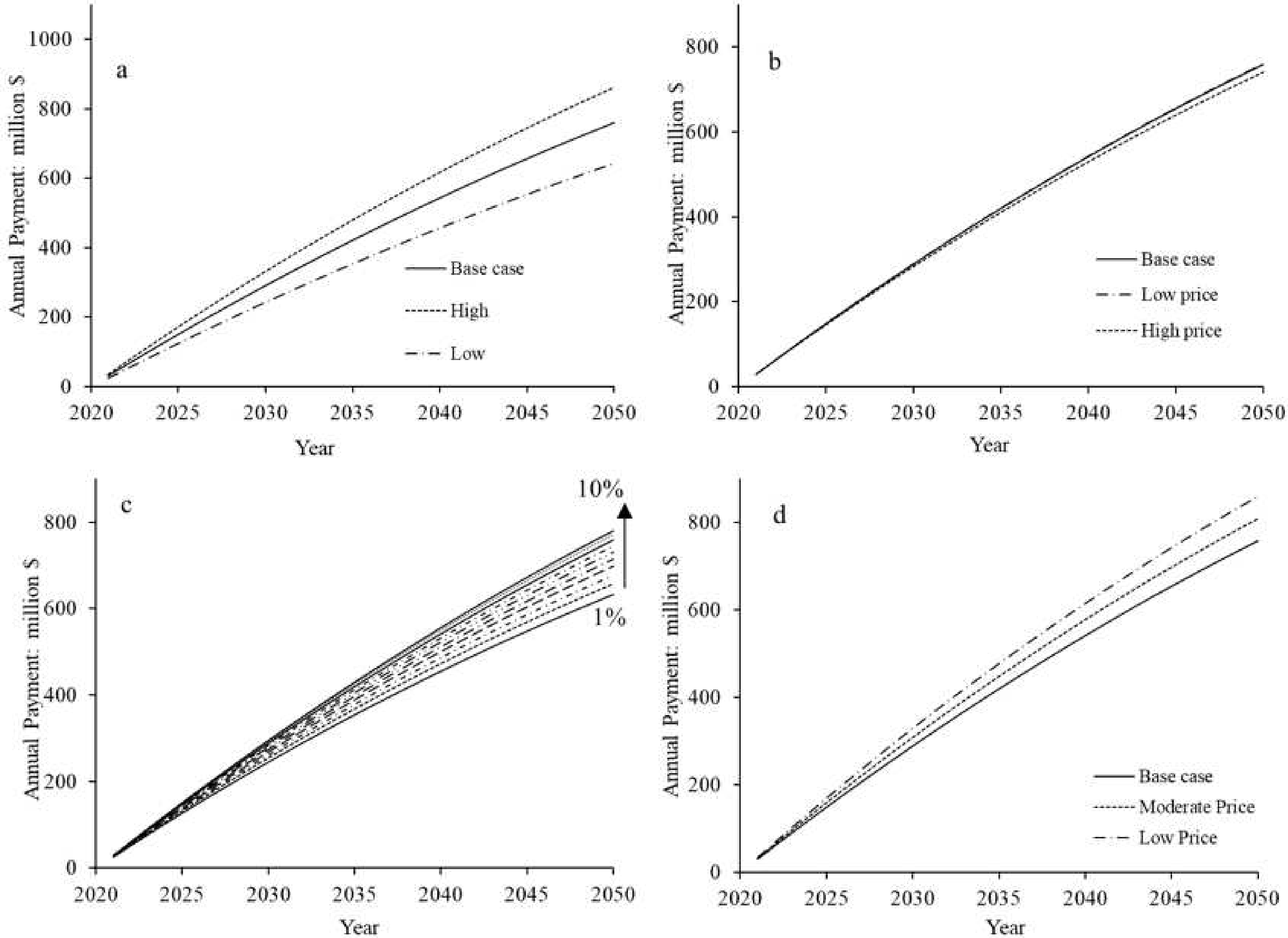



**Figure 5**

Annual carbon sequestration in the baseline within the projected period, 2012–2050




## Figure 6

Sensitivity analyses of compensatory payments on a) rubber price, b) carbon price, c) discount rate and d) traditional medicine price