Developing indicators of economic value and biodiversity loss for rubber plantations in Xishuangbanna, southwest China: A case study from Menglun township

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ABSTRACT

In Xishuangbanna, southwest China, rubber plantations are lucrative and have expanded dramatically in the past two decades, leaving little natural forest. The local government hopes to use eco-compensation mechanisms to promote forest restoration without forcing smallholders to forego profits. Based on a landscape productivity model for two management systems and given a range of prices, we assessed the feasibility of this concept by constructing a spatially explicit map of net present value (NPV) of rubber plantations. We found that roughly 7% of existing plantations generally had negative NPV, therefore opportunity costs would be negligible. But to restore forest in buffer zones along roads and rivers as recommended by the state government, more substantial opportunity costs were observed because these areas have high NPV values. Additionally, plantations situated above 900 m elevation or on slopes > 24° were not profitable and a conversion ban should be enforced. Opportunity costs and plant species biodiversity are positively correlated, so any policy to protect species-rich areas must take this relationship into consideration. Eco-compensation schemes can feasibly promote forest restoration on marginal lands and spatially-explicit mapping of NPV can provide monetary targets to adequately recover opportunity costs for smallholders.

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1. Introduction

Economic development can be achieved through holistic management of natural resources, using reasonable cost-benefit analyses that incorporate opportunity costs of both economic and ecosystem benefits. In rural areas, economic growth is often achieved through agricultural intensification and the introduction of monoculture cash crops (Manivong and Cramb, 2008; Feintrenie et al., 2010). In Xishuangbanna, southwest China, monoculture rubber (Hevea brasiliensis) plantations have expanded dramatically over the past two decades, particularly in the species rich lowlands (Li and Yuan, 2008; Qiu, 2009; Ziegler et al., 2009). Rubber is indigenous to the tropical Amazon Basin and later on was largely introduced to China in 1950s (Xu, 2006; Xu and Yi, 2013). Initially,

the Chinese central government established rubber plantations in this autonomous prefecture under the direction of the Ministry of Land Reclamation of Yunnan because natural rubber was regarded as an essential resource and critically important to national security (Xu, 2006; Sturgeon and Menzies, 2008). Partially in response to the U.S. trade embargo in the early 1950s, the Mengxing State Farm was created in the Menglun township (Fig. 1). After forestry reform in 1983, smallholder rubber plantations were initiated by villagers in Menglun assisted by technical guidance from the state-farm and government subsidies. Current proportion of rubber monoculture between smallholder and state-farm is 60–40%.

Immediate economic benefit and access to major new sources of revenue are often major drivers of rapid agricultural intensification of monoculture plantations. Rubber plantations in China are generally quite profitable and have provided considerable cash income to rural villagers in Xishuangbanna, who have few alternative sources of income (Qiu, 2009). These factors have led to the dramatic conversion of the majority of natural forests outside of protected areas to rubber monoculture plantations (Li et al., 2008; Liu et al., 2005). The strength of the economic incentive has even driven local smallholders to replace more traditional subsistence and cash crops,

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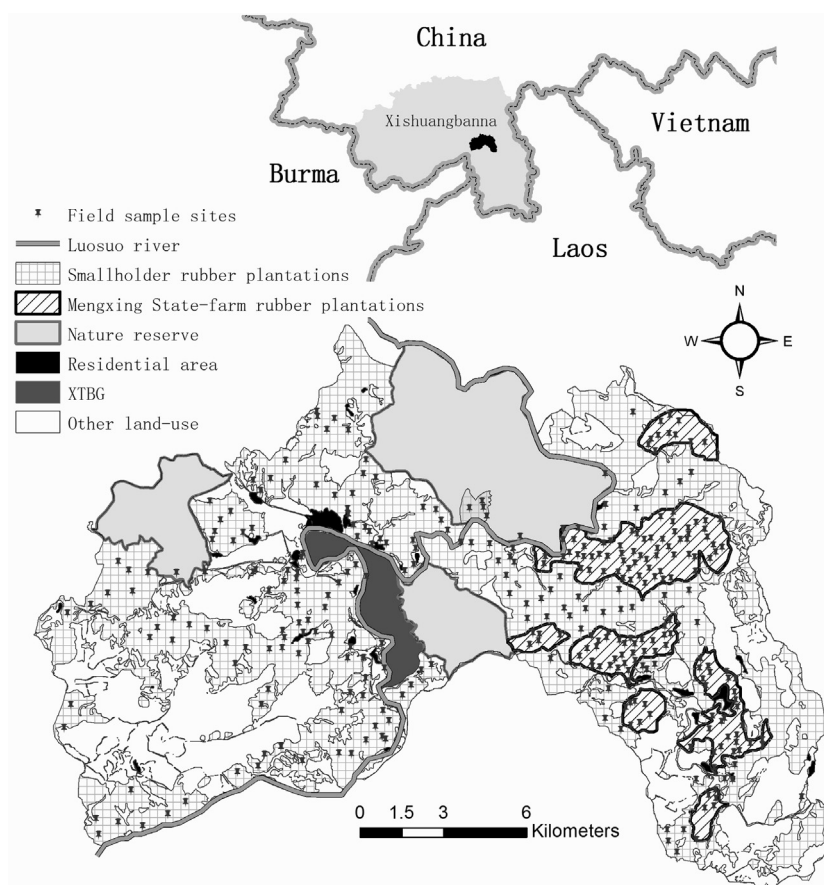
Fig. 1. Map of Menglun Township, Xishuangbanna, China, showing the major features of the landscape, including the locations of the Xishuangbanna Tropical Botanical Gardens (XTBG), developed urban areas, and protected natural forest areas. Rubber plantations managed by the Mengxing State Farm are indicated by a diagonal slash while those managed by small-holders are indicated by cross-hatching. Other land-use labeled includes fruit garden, tea garden and swidden land. The positions of our 468 sample sites for rubber yield are indicated by the black pins.

like corn, rice, and tea with rubber plantations. Additionally, the continued development of cold-resistant varieties has pushed rubber plantations into higher elevation areas and onto steep slopes, which are poorly suited for rubber production (Li and Yuan, 2008). Previous studies on the island of Hainan, China, have shown that monoculture rubber plantations on steep and hilly lands resulted in increased soil erosion (Gong, 2003), soil nutrient loss, reduced stream volume, and runoff becoming more seasonal (He and Huang, 1987; Zhang et al., 2000; Cha, 2005). Rubber trees withdraw water longer than natural vegetation during the dry season, leading to greater depletion of water in the deep soil (Guardiola-Claramonte et al., 2010).

Because rubber can be successfully grown in only a small portion of southern tropical China, the strong domestic demand for rubber combined with government policies has caused substantial natural forest loss in one of China's most biodiverse areas (Liu et al., 1998; Li and Yuan, 2008). Xishuangbanna is part of the globally recognized Indo-Burma biodiversity hotspot (Myers et al., 2000) and its natural forests contain a disproportionate fraction of China's biodiversity, given its small land area (Liu et al., 2001). The prefecture has been promoted as one of 32 territorial biodiversity conservation priorities by the Ministry of Environmental Protection emphasized in the 2011–2030 China Biodiversity Conservation Strategy and Action Plan. But rapid conversion of forest to rubber plantation now presents a serious threat to China's biodiversity (Chen and Wu, 2009; Ziegler et al., 2009). Therefore, the local government is caught between two conflicting objectives: the need for rapid economic development of the rural poor with rubber viewed as

a national security issue against the environmentally damaging effects of monoculture plantations on natural forests, ecosystem services and biodiversity.

The local government, in collaboration with scientists from Xishuangbanna Tropical Botanical Garden (XTBG), has been exploring policy mechanisms to control forest conversion and provide economic incentives for forest restoration. The environmental impact of rubber plantations is significant but the incurred costs are difficult to quantify because they are external to economic accounting, particularly the loss of water storage capacity (Cha, 2005), increased soil erosion (He and Huang, 1987; Zhang et al., 2006) and environmental degradation (Zhang et al., 2000; Qiu, 2009). Additionally, these hidden costs take many years to reach their full impact, e.g. reductions in foggy days from the 1950s to the present (Gong and Ling, 1996; Wu and Yang, 2001; Zhou et al., 2006) and water shortage at high elevations since 2000 (Wu and Yang, 2001; Yang and Qin, 2009). Developing policy to create the proper incentives for sustainable management and protection of natural forest is difficult (Engel et al., 2008; Kelsey and Carolyn, 2008), particularly given the rapid development of China's market economy and growing autonomy of rural landholders through China's forest tenure reform (Rozelle et al., 2003; Xu, 2008).

To establish an economic indicator for rubber planting area and as a first step toward understanding the financial feasibility of any policy to promote reforestation in Xishuangbanna, whether based on compensation schemes or ecosystem service evaluation, we performed an analysis of the productivity and net present value (NPV) of rubber plantations in Menglun Township, Xishuangbanna. NPV

is a time series analysis of cash flow for a given investment, comparing the initial value of the investment to the expected reward over the investment's lifespan, given some social discount rate (Butler et al., 2009). The township represents an ideal location for the study because Mengxing State-Farm is the one of oldest managed rubber plantations in China and the ongoing conversion of natural forests into rubber plantations by independent smallholder has been dramatic, including considerable encroachment on marginal lands. This allows direct comparison of rubber productivity between two well-established management systems, due to Mengxing State-farm being a good example of state farmed rubber, it has became a showcase in the region.

To assist the local government's initiative to develop a detailed and reasonable policy to promote reforestation, we generated spatially explicit maps of the net present value (NPV) of rubber plantations under both the state-farm and smallholder management systems, for the entire township. From these maps, we identified those areas where rubber plantations are least likely to be profitable over 25 years and we determined the scale of economic incentive required to promote forest restoration. Additionally, we directly compared landscape level indicators of biodiversity (Liu et al., 2007) to rubber NPV to address whether sites with high diversity directly conflict with sites of high profitability. As maintenance of biodiversity is central to most conservation schemes, identifying locations where stated management objectives directly conflict will be useful in resolving these issues and establishing necessary compensation mechanisms.

While the use of eco-compensation schemes or payment for ecosystem services are attractive ideas, if the profitability of rubber plantations is substantially greater than benefits provided by these mechanisms, then market-based incentives are likely doomed to fail. In this case, more top-down control mechanisms would be required to restore and maintain natural forests with their associated ecosystem services and high levels of biodiversity providing adequate justification for these additional funds. For example, the Chinese State Forestry Administration has recommended that monoculture rubber plantations within a 200 m wide buffer zone on either side of main roads, highways and rivers be replaced with natural vegetation (China SFA, 2003). In these "buffer zones", profitability may be high and therefore more direct payments may be necessary. On the other hand, the profitability of rubber, particularly on marginal lands, may be exaggerated and market-based policies for eco-compensation may be reasonably competitive in these "low productivity sites", regardless of biodiversity indicators. Our spatial map of projected rubber NPV can assist local governments in evaluating these issues.

We also ask several other key questions related to these issues: What is the spatial variability in net present value or rubber plantations across the township? What is the opportunity cost associated with two types of targets for forest restoration; 1) "low productivity sites" where NPV is generally negative and 2) "buffer zones" of 200 m along major roads, highways, and rivers, as recommended by the Chinese State Forestry Administration? How does our model for rubber NPV compare with landscape- level indicators of biodiversity and where do these two values conflict spatially?

2. Methods

2.1. Study area

Menglun Township (total area = 335 km^2) is located in central Xishuangbanna, south-west China, which borders the People's Democratic Republic of Laos and Myanmar (Fig. 1). Elevation ranges between 517 and 1541 m with an average temperature between 20° and 22.5° and the highest summer temperature being

between 25° and 27°. Annual precipitation varies between 1200 and 1800 mm, with a wet season lasting from May to October during which 90% of the precipitation falls. The Xishuangbanna climate is quite suitable for rubber trees and they grow faster than on the island of Hainan and in most other Southeast Asian countries (Huang, 2004b), even though the trees shed their leaves for much of the dry season (Guardiola-Claramonte et al., 2010; Huang, 2004b). In 2005, rubber plantations occupied 151 km^2 in Menglun Township, covering 45% of total land area, which belong to nearly 10,000 households, rubber-tapping workers and farmers were employed in plantation work (Menglun Government annual report, 2010).

2.2. Developing a landscape model of rubber productivity

There were three stages in the development of our spatially explicit model for rubber productivity: (1) compiling data layers to describe environmental variation; (2) direct field measurements of rubber yield; and (3) creating a predictive model for rubber productivity, based on the spatial correlation between the two previous data layers. The data layers and field measurements included the complete range of variation within the entire township (see Fig. 1 for sampling points of rubber yield).

2.2.1. Environmental descriptors

Rubber growth and yield is strongly promoted by high precipitation, high and constant temperatures during the rubber tapping season, particularly on flatter slopes at lower elevations (Zeng, 2004). To capture these environmental variables, we downloaded a digital elevation model (DEM) of the study site from the US Shuttle Radar Topography Mission website (SRTM, http://srtm.csi.cgiar.org/), which was re-sampled to 100 m^2 resolution. The data layers for elevation, slope and aspect were created from the DEM. Precipitation and temperature data were obtained from the WorldClim database (Hijmans et al., 2005; http://www.worldclim.org/) and soil characteristics (such as type, depth and pH) were extracted from the Harmonized World Soil Database (Nachtergaele et al., 2008; http://www.fao.org). Ultimately, we used 46 environmental and climatic variables to develop our rubber productivity map.

2.2.2. Rubber yield data

Between May and November of 2009, we sampled 302 state-farm sites and 166 smallholder sites chosen in a stratified random fashion to cover most of the landscape variation in elevation, slope, and aspect within Menglun Township. Because more than 90% of plantations in Xishuangbanna are composed of just two rubber tree varieties (GT1 and RRIM600), we restricted our sampling to sites where these varieties were dominant. The following information was recorded at each site: GPS location, tree density, tree age and observed daily productivity. Because rubber trees are planted on row terraces, the distance between trees along each contour is typically much shorter than between contours, so we measured the distance among four trees at each point, both along and across rows. Typically, on state-farm plantations, the "along contour" distance was 2.5 m and the "across contour" distance was 8–10 m while the distances were typically shorter on smallholder plantations (1–2 m and 4–6 m, respectively). Therefore, tree densities on state-farm sites were considerably lower than on smallholder sites (~495 trees per hectare compared to 580–850 trees per hectare, respectively).

We estimated tree age by counting the number of tapping-scars present on the four trees nearest the sampling point. Rubber trees are tapped systematically, from top to bottom, down one side and then down the other. We could then calculate how many years the tree has been tapped by dividing the number of scars by 120 scars/year, which is the average number of harvesting days. Trees in Menglun are usually first tapped when they are 8 years old,
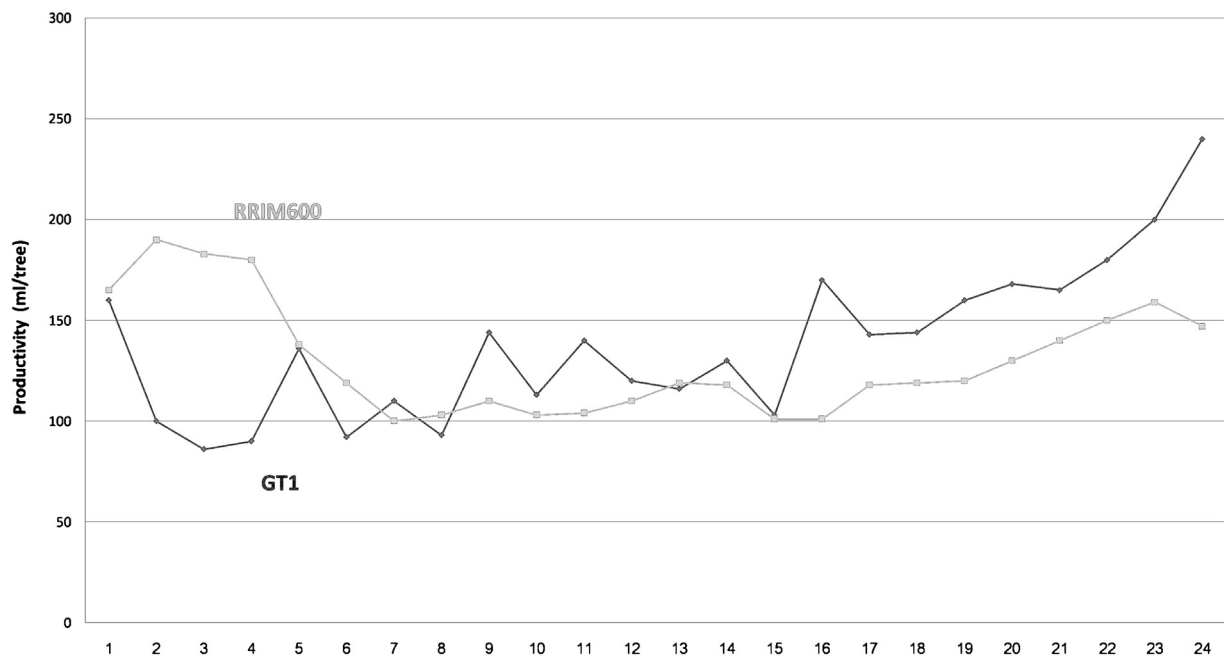
Fig. 2. Seasonal variation in daily yield for the two main varieties of rubber tree (RRIM600 and GT1) cultivated in Menglun Township, China. These curves were created from over 20 years of field observation by the Yunnan Tropical Crops Institute (Huang and Luo, 2004). These curves were used to estimate total annual yield for each of our direct observations of rubber yield at 468 sample sites (see Fig. 1).

therefore tree age = number of scars/120 scars per year + 7 years. We recorded the volume of harvested latex in millimeters for each tree to estimate the daily yield. Four trees were measured per sample site and an average yield for each site was calculated. We used a quadratic equation to fit annual rubber yield (Fig. 2) over the eight month tapping period (Huang, 2004) to our data, because the two varieties of rubber tree (GT1 = Y_{GT1} and RRIM600 = $Y_{RRIM600}$) vary in their seasonal yield. The annual productivities of the two varieties were then estimated by Eqs. (1) and (2), given our direct measurements of yield:

$$Y_{GT1} = \sum_{1}^{24} 0.37x^2 - 5.2x + 127.2 \qquad (1)$$

$$Y_{RRIM600} = \sum_{1}^{24} 0.54x^2 - 14.5x + 200.7 \qquad (2)$$

To simplify the calculation, we chose x to be 1–24 (every 10 days is 1 from late of March to mid-November). For example, if we collected rubber yield measurements on the 6th of June, $x = 8.6$ as calculated by $x = (\text{month} + \text{data}/30) \times 3 - 10$. From Huang's fitting equation, we found that the contribution of x to the yield of each tree per year varies from 3% to 7% for GT1 and from 3% to 6% for RRIM600. Additionally, the average content of rubber latex mass varies slightly between the two varieties, 32% for GT1 and 30% for RRIM600.

Therefore, the annual yield per hectare (Y_{Ann}) is given by

$$Y_{Ann} = \frac{m}{C_x \times D_{rt} \times T_{rt}} \qquad (3)$$

where m represents the yield per tree every ten days; C_x is the percentage contribution of x to the annual yield per tree; D_{rt} is the tree density of the plantations; and T_{rt} is the thickness of the rubber latex, which is used to calculate the rubber latex mass. The value of m is calculated differently for state-farm and smallholder plantations, where m is $V_D/0.4$ and $V_D/0.2$, because trees are tapped five times every ten days on smallholder but 2.5 times in state-farm (see Section 2.2.4 below). Additionally, because smallholder farmers do not tap on rainy days, the annual yield of latex might

be even lower than predicted by the current model. Finally, we estimated the productivity of the rubber trees based on observed daily yield, and we compared the estimated quantiles with the 34 years of recorded data from the state farms. We found 27 out of 34 of the real data lie inside the 95% confidence enclosed by the 0.025 and 0.0975 quantiles.

2.2.3. Spatial modeling of rubber yield

The rubber yield on state-farm plantations is considerably larger than the yield from smallholder plantations, primarily due to management practices developed over 50 years of agricultural research into rubber production as well as greater investment in equipment and staff training. The major differences in management practice are related to tapping frequency and consistency, chemical inputs, and optimal tree densities. One rather simple innovation involves shielding latex collection during rainstorms, allowing state-farm tappers to work throughout the rainy season, while smallholder tappers stop harvesting on rainy days, which are frequent during the wet season.

Additionally, a yield stimulant, the chemical 'ethephon', is regularly used on trees older than 10 years (Ao, 2004a; Nair, 2010; Wang and Chen, 2004). This stimulant basically doubles rubber production and state-farm trees can be tapped once every four days to obtain the same yield as smallholder trees being tapped every other day. This reduction in tapping frequency and intensity causes less bark damage, extending the life span of the tree to roughly 35 years compared to 25 years on the smallholder farms. Finally, the density of trees per hectare on smallholder farms is often twice as high compared to a state-farm plantation, as described above. Huang (2004a) reported that 495 rubber trees per hectare is the optimal density, which is lower than any tree density measured on a smallholder plantation. Smallholder planters can also obtain subsidies from local government for planting (3 RMB/seedling) which may encourage overstocking.

Because yield differed substantially between the two management systems, we developed separate models for state-farm and smallholder plantations, incorporating the differences into the appropriate parts of the model to produce landscape level economic

values for rubber plantation in each management system (Fig. 1). Because abundant previous research had demonstrated that rubber productivity varies with several environmental factors, including tree density (Huang, 2004a), variety (Ao, 2004b; Pan, 2004), direct solar radiation, slope, aspect, temperature (Ao, 2004b; Ao et al., 2004; Huang and Luo, 2004), rainfall (Wang and Chen, 2004), soil nutrition (Li, 2004), soil pH and others (Zeng, 2004), we built a stepwise regression model to analyze the relationship between environmental factors and rubber productivity, using the 46 variables compiled from numerous sources described above. In order to explore the differences between the two management systems, we performed the analysis separately on the smallholder and state-farm samples. One hundred sites were randomly selected from each management system as a training set, using the remainder of the original 302 state-farm and 166 smallholder sites (Fig. 1). We then analyzed the rubber yield against environmental descriptors by spatial multi-variables linear regression, all analyses were conducted using R software (http://www.r-project.org/) and spatial analysis of ArcGIS 9.3.

We then mapped this predicted rubber yield onto a land-cover map of Menglun, generated from a Landsat ETM+ (Enhanced Thematic Mapper Plus) image taken in 2005 that was downloaded from the Global Land Cover Facility (http://glcf.umiacs.umd.edu/data/landsat/). Detailed land-cover maps for 1965 and 2007 obtained from the Menglun Forestry Department provided training data for a supervised maximum likelihood classification of the satellite image. The resulting map was further validated against GPS-based ground-truth measurements taken in 2009. Rubber plantations have a distinct pattern on the Landsat images because of the terracing and regular row planting, making them clearly distinguishable from natural forests (Li and Fox, 2012). We selected ten training points for each of nine land use classes. Overall, classification of land use in the study area proved to be straightforward, and results from the supervised classification showed an 89.3% accuracy with an average Root Mean Square Error of less than a half-pixel after rectifying to Ablers Conical Equal Area projection system.

2.3. NPV of rubber plantation

In order to reveal the economic value of rubber plantations, we calculated their spatially-explicit Net Present Value (NPV) of over 25 years across Menglun township using Eq 4, described below. Because rubber productivity is substantially different between state-farm and smallholder plantations, we estimated NPV separately for the two management systems, as described above. We used the following equation to calculate NPV:

$$NPV = \frac{[\sum_0^{25}(B_i - C_i)]}{(1+r)^i} \qquad (4)$$

where B_i is the expected benefit of a rubber plantation over 25 years; C_i represents the cost of investment of rubber plantation over 25 years; $i = 0,1,2\ldots25$, lifespan of the investment which we assumed to be the rotation interval commonly found among smallholder plantations (25 years), where $i = 0$ is the time of establishment of rubber plantation; and r is the social discount rate, ranging from 1 to 10%.

To generate the rubber productivity models into B_i, we use the following productivity curves for the two different management systems. Rubber productivity was modeled according to the age of the rubber trees through the 25-year rotation cycle of smallholder managed plantations. The curve was generated from data recorded by the managers of the Mengxing State Farm:

$$State\text{-}farm_{rubber} = -20.03X^2 + 742.2X + 565 \, (R^2 \text{ is } 0.61); \qquad (5)$$

productivity of smallholder rubber plantations for SH was gained directly from our field observations:

$$Smallholder_{rubber} = -13.30X^2 + 261.4X + 300 \, (R^2 \text{ is } 0.84), \qquad (6)$$

where X represents rubber tree age, with trees being tapped from 8 to 25 years of age.

The total benefit of the investment (B_i) is then the product of the year-specific productivity multiplied by the price of natural rubber. We examined a range of rubber prices in our model. Currently, the highest price of rubber in the market is $6.3/kg (January 2011) and to illustrate the impact of changing commodity prices on potential returns, we calculated NPV using rubber prices ranging from 0 to $10/kg. We used $100 = 657RMB (March 2011) as the currency exchange rate. We calculated the projected productivity of rubber plantations at a resolution of 1 km.

A final benefit is gained at the end of the plantation's rubber productivity, because the timber can be sold. Trees harvested from state-farm sites are typically larger because of their greater age and better management. The average price of timber from state-farm plantations ($44/tree) is twice that for smallholder plantations ($22/tree). This price benefit must be discounted against the return period which is longer in the state-farm case (35 years as opposed to 25 on the smallholder farms). We added this value at the end of the time series, discounted over the rotation period.

The total cost of the investment (C_i) also differed substantially between the two management systems. Costs of for state-farm rubber plantations were based upon the record books of Mengxing state-farm, including cost of rubber seedlings, labor force, chemical, fertilizer, worker training, and equipments and tools for plantations management. For the cost of smallholder, we excluded the cost of rain protection shields, ethephon treatments, labor force and workers training cost, so that the total cost of smallholder is about 70% of state-farm costs. In order to simplify the comparison between the cost of state-farm and smallholder, we separated the establishment cost, which is the total cost from years 1 to 7 of rubber plantations, state-farm is $4384/ha, smallholder is $2689/ha, and management cost, which starts in the eighth year when tapping begins. Finally, the material cost of state-farm is $15,860/ha and smallholder is $11,102/ha.

Labor costs are higher on smallholder plantations because an experienced state-farm worker can manage 3.1 ha of rubber trees compared to 1.3 ha for a smallholder farmer, and because trees are tapped twice as frequently by smallholders (d/4 in state-farm and d/2 in smallholder). Ongoing costs of management are lower on smallholder ($2.1/tree) than on state-farm farms ($2.9/tree), because state-farm farmers typically use the rain protection shields for continuous harvest during the rainy season and treat the tree bark with plant growth hormones.

Finally, the social discount rate reflects a society's relative valuation of today's well-being versus future well-being (Zhuang et al., 2007) and incorporates uncertainty about the future into the calculation. Interest rates in China are currently quite high, indicating a level of uncertainty in the market. A national discount rate of 8% was suggested by the Asian Development Bank (Zhuang et al., 2007), but we explored discount rates ranging from 1 to 10% to discover the sensitivity of the NPV for rubber plantations as policy changes. Most results are presented using the recommended rate of 8%. Final NPV was calculated in MATLAB (version 2010b: http://www.mathworks.com/products/matlab/).

2.4. Biodiversity estimation

Since the beginning of state rubber plantations in the 1950s, the landscape has been classified into three categories according to environmental conditions and vegetation type. Lowland rain forest areas were considered the best location for rubber plantations,
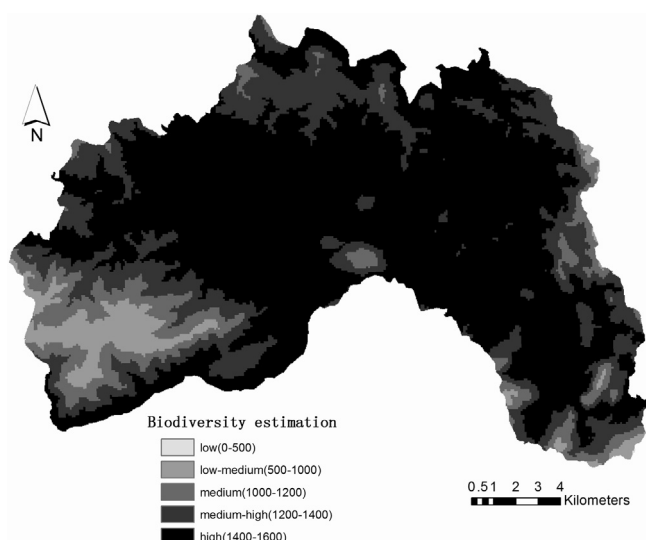
Fig. 3. Biodiversity estimation from Liu et al. (2007), the number in the bracket is the species diversity of seed plants.

Table 1
Regression coefficients for the NPV models constructed for the SF and SH sites, where P-values are significant at. = 0.1, * = 0.05, ** = 0.01, *** = 0.001.

Variables	State-Farms		Smallholder Farms	
	Coefficients (A_n)	P-value	Coefficients (a_n)	P-value
Constant	974.9	***	461.9	*
Slope	−0.6	***	−0.9	***
Aspect	0.2	***	0.1	***
Tree age	0.2	.	2.9	***
Soil AWC (mm)	0.1	.		
January rainfall	−24.8	***	−13.3	*
February rainfall	−8.7	***	−10.7	*
April rainfall	2.5	.	−5.8	*
June rainfall	3.0	.		
July rainfall			−8.6	***
August rainfall		***	−6.0	***
September rainfall	4.9	***		
November rainfall			−13.3	***
December rainfall			−11.7	*
Annual rainfall	−1.7	***	4.0	***
Soil pH	2.0	*		
Soil sodicity			−5.1	*
January MT	−44.0	***		
May MT	95.5	***	17.8	*
August MT			10.8	.
September MT	−35.0	*		
December MT	−23.2	.	15.0	*

Soil AWC means available water capacity.
January MT stands for mean temperature in January.

and seasonal rainforest and montane rain forest were second best, followed by evergreen-broad-leaf forest (Zeng, 2004). This classification system indicates a direct conflict between rubber plantation development and biodiversity conservation in Xishuangbannna, as biodiversity richness follows the vegetation type ranking (Liu et al., 2007).

Previous studies have demonstrated a strong negative correlation between elevation and species diversity of seed plants in Xishuangbanna, which is greatest at 500 m asl where nearly 1600 species are found in lowland rainforest. Species diversity slowly declines with increasing elevation until less than a hundred species are found at elevations of 2100 m asl (Liu et al., 2007). The predictive equation for species diversity (SD) as it varies with elevation in Xishuangbanna is: SD = −1.278 (Elevation)^2 − 88.3 (Elevation) + 1766 (R^2 = 0.97). We use this predictive equation to estimate the maximum potential gain in species diversity when the targets for reforestation identified in this study are converted back to natural forest (Fig. 3).

3. Results

3.1. Spatially explicit map of NPV

Site- specific NPV was strongly affected by aspect, slope, age of trees, rainfall and mean temperature (Table 1). Predictably, plantations with a southern aspect had higher productivity due to the increased solar radiation. Steep slopes were significantly lower in productivity, probably due to poor soil nutrients and water status. Latex productivity also varies with tree age, increasing until middle-age (18 years in smallholder, and 27 years in the state-farm) and then declining slowly. The model coefficient of tree age is 0.2 in the state-farm but 2.9 for smallholder; Grist et al. (1998) demonstrated that tree girth, and thus loosely tree age, have a generally positive relationship with rubber latex productivity. Therefore, given the much lower coefficient in the state-farm, the use of ethephon and fertilizers appears to reduce the effect of tree age in state-farm plantations.

The predictive power of the two models of rubber productivity for each management system differed substantially when applied to the entire township. The state-farm sites, chosen specifically by early planters to maximize productivity, were concentrated on flat land at low elevation, while the range of environmental variability across the township on smallholder sites was considerably larger

than for the state-farm sites, particularly for elevation. The map of NPV rubber in Menglun was based on current distribution of each management system in the township, i.e. the state-farm model is only used for the areas managed by the state farm, likewise for the smallholder model. To test the fit of the spatial multi-variables linear regression model for each management system, we used 30% of the data on rubber yield as test data, while the other 70% was used to create the predictive model. For state-farm data, the mean error rate, which was measured as the mean of the absolute ratio of fitting error to true value, was 7.3% while for smallholder data, the mean error was 11.1%. The larger error rate in the smallholder model probably reflects the wider range of management practices and wider environmental conditions on smallholder farms compared to the more localized state-farm.

3.2. Forest restoration targets

Clearly, some sites that have already been converted into plantations are not suitable for rubber as they consistently have a negative NPV. Even assuming high rubber prices, these can be designated as "low productivity sites" (Fig. 4). These sites can therefore be targeted for forest restoration on the basis of economic indicators alone, regardless of biodiversity value. From our rubber NPV model for each management system, we determined that if the average rubber productivity falls below 250 kg/ha year for the state-farm and 170 kg/ha year for smallholders, a plantation will be vulnerable to market fluctuations and will be profitable only under the most favorable conditions, given an average cost of $810/ha year for the state-farm and $560/ha for smallholders. If these plantations are designated as forest restoration targets, the local government can easily afford to compensate the farmers' loss, because opportunity costs are low. By overlaying the location of existing rubber plantations on the NPV map, we can identify the areas with a negative NPV, which comprise about 7% (1000 ha) of the rubber plantation area, which is 100% owned by smallholders, as the best targets for a forest restoration program (Fig. 4).

On the other hand, the total opportunity costs associated with the "buffer zones" to replace monoculture rubber plantations
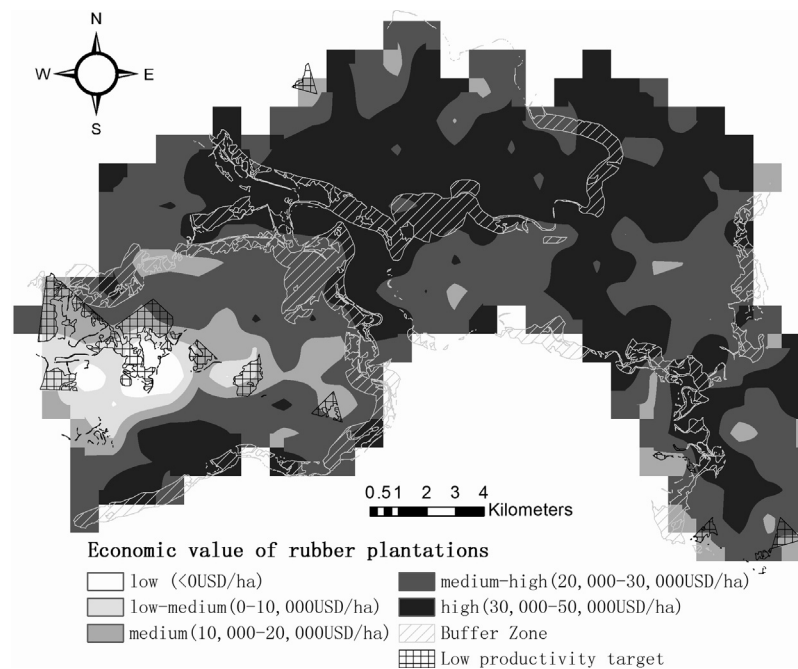
Fig. 4. Spatially explicit NPV of rubber plantations in Menglun township, China, for the Menglun scenario, where productivity is predicted by the appropriate regression model for the management system practiced in each site. Two types of forest restoration targets are illustrated: "low productivity sites" are represented by areas filled with a white grid while "buffer zones", along the main roads, highways, and rivers, are represented by areas filled with white diagonal lines.

within a 200 m wide buffer zone on either side of main roads, highways and rivers with natural vegetation as recommended by the Chinese State Forestry Administration (Fig. 4) (China SFA, 2003) will range from $31.6 to 320 million USD given rubber prices of $1–10/kg, while the average per hectare opportunity cost ranges from $8136–82,389/ha, respectively, over 25 years. Given the average price of rubber of $3.4/kg, the opportunity costs for these buffer zones would be ~$19,800/ha. The total land area in Menglun that lies within this proposed buffer zone equals 3884 ha (12% of the township's land area) and current is under rubber, of which 70% is below 800 m and before rubber it was classified as tropical seasonal rainforest (Zhao et al., 1985; Zhu, 2005). Because these areas are quite suitable for rubber plantations and have higher NPV, this proposal will require a considerably larger amount of compensation to remove them from production.

Finally, we sampled NPV of the Menglun scenario from our map at more than 200 points, using the interstices of a rectangular grid (1.5 km × 1 km). When these values were modeled against elevation, slope, aspect, distance from the main Luosuo river, distance from highway, roads, distance from villages and township of Menglun, we observed that elevation ($r^2 = 0.42$) and slope ($r^2 = 0.45$) are negatively related to NPV (Fig. 5). Even when the natural rubber price is high ($10/kg), plantations at elevations above 900 m (He and Li, 2004; Xu et al., 2013 (this issue); Nguyen, 2013) or on a slope higher than 24° were not profitable, which is subset of negative NPV (7% of rubber area in Menglun township) of rubber plantations.

3.3. Forest restoration targets and biodiversity gain

Given the correlation between elevation and plant species diversity observed in Xishuangbanna (Liu et al., 2007), the "buffer zones" along main roads, highways and rivers have the potential to recover a substantially larger amount of species diversity than the "low productivity sites", indicating that there is a positive relationship between biodiversity and rubber NPV. Given the range of elevation in the buffer zones, the maximum total number of plant species that could be recovered would be 1500 compared to 1000 plant species
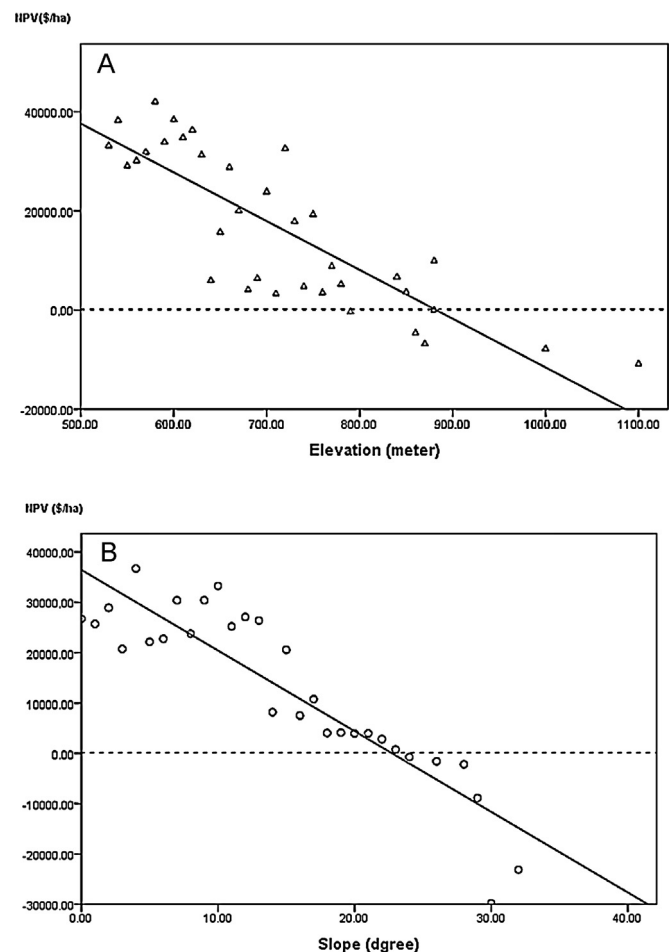

Fig. 5. Relationship between modeled NPV, given a rubber price of $10/Kg, and (A) elevation and (B) slope.

Table 2
The opportunity cost in rubber NPV in Menglun township, China of forest restoration in thousands of USD/ha over 25 years, given the current rubber price, SF management system, and various different discount rates (%), and the maximum potential biodiversity gain from forest restoration, given a simple model of species diversity and elevation (Liu et al., 2007). "−NPV targets" refers to those areas with a negative NPV while "BZ targets" refers to those areas recommended by the state government to form buffer zones along roads and rivers.

	Opportunity Costs				Gain in biodiversity
	1%	4%	8%	10%	
−NPV targets	1	0.8	0.3	0.2	≈1000
BZ targets	343	211	82	52	>1500

in the low productivity sites (Table 2). These sites would also provide the greatest benefit in biodiversity conservation, thus providing additional justification for this increased investment and a potential subsidy-based compensation mechanism. We estimated that 10% of rubber farmers, equivalent to 1000 households, who are located in buffer zone (5%) and low productivity sites (5%) would be affected by the biodiversity gain program in the future.

4. Discussion

China is among the world's top consumers of natural rubber and the central government has listed rubber as a key strategic natural resource. Domestic production of rubber in China is limited to tropical areas rich in biodiversity, i.e., Xishuangbanna and Hainan. Rapid conversion over the last two decades has left little remaining natural forest outside of protected areas (Liu et al., 2005, 2006; Li, 2007; Li et al., 2008; Qiu, 2009; Ziegler et al., 2009). Simultaneously, Xishuangbanna has been promoted as one of 32 terrestrial biodiversity conservation priorities by China's Ministry of Environmental Protection and emphasized in China's Biodiversity Conservation Strategy and Action Plan for 2011–2030 (China, 2010). These priorities conflict with the strong market and high demand for rubber that has generated considerable cash revenue for rural smallholders who frequently have limited alternative sources of income. These economic indicators of rubber plantation value are also generally in direct conflict with landscape-level biodiversity at the spatial scale of a single township, as we have shown. Under the current forest tenure policy of China (Liu and Cannon, 2011), farmers have been given autonomous "use rights" over forest land previously managed collectively, which will allow them to choose how they manage their land. Therefore, the local government's objective of promoting forest restoration through eco-compensation mechanisms faces a number of challenges, particularly if their policies impose large opportunity costs without adequate and direct financial compensation to the effected smallholders.

4.1. Indicators of economic value from rubber plantations

Previous studies have shown that the opportunity cost of protecting tropical biodiversity could be very high in the future because of increased per capita consumption by human populations and the continued expansion of cash crops and monoculture plantations, e.g. oil palm, rubber, and eucalyptus (Butler, 2008a,b; Butler et al., 2009; Guo et al., 2002; Koh and Wilcove, 2008; Xi, 2009). While there is a great deal of interest in compensation schemes based on carbon sequestration and carbon trading, early evaluations indicate that the carbon market cannot compete with the profitability of oil palm (Butler et al., 2009). However, our spatially-explicit map of rubber plantation NPV across Menglun township as an indicator of their economic value, based on a model of landscape- level rubber productivity that incorporates the two different management systems present in the township, the local government will be better equipped to resolve these conflicting interests through the

selection of restoration sites that will impose the least opportunity cost ("low productivity sites") and the accurate estimation of compensation where ecosystem value is high but difficult to quantify ("buffer zones"). For low productivity sites, roughly 7% of current rubber plantations were projected to have a negative NPV over the next 25 years, making them obvious targets for forest restoration as these plantations represent lose-lose situations, where ecosystem services and biodiversity are lost while no long-term financial gain is achieved. From our field observations, all of the sites with a negative NPV are currently owned and managed by smallholders and most are young plantations, established after 2001 on sites with unfavorable environmental conditions. They are also generally distant from central rubber markets in Menglun and will incur high transportation costs, a further negative factor not included in the current NPV analysis. Forest restoration of these sites would likely improve water storage capacity and management, helping to recover plant species diversity in the region.

4.2. Biodiversity indicators

The opportunity cost of reforestation on the low productivity sites described above would only amount to $0.3 million over the next 25 years or approx $300/ha ($12/ha/year), which is relatively trivial. However, farmers under low productivity sites are expecting they can gain rubber profitability with further intensive input, and they must fail first before they realize that the rubber is not profitable there, and this cycle could easily take 10–15 years. Even though these areas do not provide the greatest biodiversity benefit (Fig. 3), the gains in species richness would still be substantial and beneficial, particularly as species composition in these sites is different than the species-rich lowlands (Zhu, 2005). In general, if smallholder plantations were placed under state-farm management practices, the overall productivity and profitability of existing rubber plantations would increase, potentially removing some of the pressure for forest conversion and providing more tax revenue to fund restoration in sites with low productivity, thereby increasing the threshold for a feasible eco-compensation scheme. Additionally, our results indicate that areas above 900 m elevation and on slopes steeper than 24° were not profitable. We strongly recommend that existing rubber plantations in these settings be restored to forest and that a clear ban against conversion of these sites to rubber plantation be strictly enforced.

In Xishuangbanna, natural areas with the highest alpha plant species diversity (Liu et al., 2007) coincide with the areas with the highest NPV of rubber plantations (Fig. 5). The "buffer zones" recommended by the Chinese State Forestry Administration will impose considerable opportunity costs for smallholder managers while also providing the best opportunity to maintain species diversity and important ecosystem services. To fulfill this recommendation, the local government will have to find the right balance between economic development and biodiversity conservation, recognizing that in this situation a market solution will not succeed because the short-term profitability of monoculture rubber plantation is much stronger than any perceived benefits from natural forest protection or forest restoration. If commodity prices of natural rubber continue to rise, these opportunity costs will only increase. Our NPV map can provide these local officials with a reasonable estimate of the compensation necessary to promote forest restoration and protection but further education and outreach about the importance of the ecosystem services and biodiversity maintained by natural forest will be necessary. Reforestation of the proposed buffer zones would promote biodiversity, habitat connectivity, and reduce soil erosion into the water system, valuable ecosystem services not included in the current evaluation. Attempts to quantity these ecosystem benefits should be a priority and the results clearly explained to smallholders. Finally,

the local agricultural extension agency should focus on improving management of existing smallholder plantations to increase the rubber yield across the prefecture.

Even though future predictions about the price of rubber are optimistic, both the local government and rubber plantation managers should be aware of the volatility of natural rubber prices and even its potential replacement by other sources of rubber. Because of the concern about the potential disastrous outbreak of disease in monoculture plantations of *Hevea brasiliensis*, alternate sources of natural rubber are actively being explored (van Beillen and Poirier, 2007) and alternative synthetic sources could possibly be developed (IISR, 2008). The volatility of the market is particularly important for crops like rubber, because of the long rotation cycle and the extended period of time before the rubber plantation becomes profitable after initial establishment. Conversion of forests now, while prices are high, could become tragic examples of the effects of a shifting global market, if the natural rubber market collapsed, as the ecosystem services of natural forest would be completely lost without any economic benefit. Policy makers should consider contingency plans, in case of market failure, and these possibilities should also be communicated to rural smallholders, who have limited experience with market economics. One possible contingency plan is the development of "jungle rubber", where monoculture is exchanged for a mixed agroforestry system, but again, promoting this more environment-friendly management system will require sound incentive policies as the reduction of smallholder's income comes with the declination of their land availability (Gouyon et al., 1993). The Xishuangbanna government has assembled multi-disciplinary teams of experts from XTBG, Yunnan Society of Tropical Crops, and Yunnan institute of Agricultural Engineering Research and Design to compose a 5-year plan (2011–2015) for Bio-industries in Xishuangbanna, in order to diversify the benefits from ecosystem and agriculture for local communities.

5. Conclusions

Our study highlights the spatial variability of economic benefits from rubber. Even though conversion can lead to substantial profits, the ultimate return is site-specific. A detailed spatially explicit analysis can identify those locations where NPV is negative or vulnerable to market fluctuations and eco-compensation mechanisms will work effectively. Additionally, because biodiversity richness and economic benefit are often highest in the same locations, our approach provides a direct monetary indicator of the compensation necessary to meet the stated conservation goals. Ultimately, our research can provide a spatial scheme of minimizing opportunity costs to the local community of smallholders while maximizing biodiversity conservation for the wider community of people in future land-use planning.

Local policymakers need to look for market-based solutions for forest restoration, which may be more sustainable than previous mechanisms based on direct governmental subsidies. These mechanisms have not worked well because the payments have typically been low compared to the profitability of the cash crops. Market-based solutions can be funded by taxing agrochemical inputs and pollutant emissions from rubber processing factories, carbon sequestration and pre-harvest credits, and other payments from the environmental market. The final incentives can be based on appropriate pricing of opportunity costs to adequately encourage smallholder farmers to protect forests. The latest Forest Property Reform (http://www.forestry.gov.cn/) is an opportunity for decision-makers to prove the possibility of forest restoration on selected targets by giving appropriate and fair eco-compensation. Moreover, we have the following recommendations:

1. Given the low opportunity costs for this program, forest restoration programs can be created on sites where rubber NPV is negative or vulnerable to market volatility for bring back biodiversity in the future;
2. Conversion of forests to rubber plantations above 900 m elevation and on slopes steeper than 24°should be banned; and
3. "Jungle rubber" should be developed on both state-farm and smallholder plantations, particularly in those locations with high ecological values for watershed protection, soil erosion reduction, and biodiversity conservation. Mixed jungle rubber can incorporate high-yield rubber varieties with other economically valuable species to reduce the economic loss to smallholder and state-farm farmers (Gouyon et al., 1993).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2013.03.016.

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