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Past, present and future land-use in Xishuangbanna, China and the implications for carbon dynamics

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Abstract

Land use/land cover change is an important driver of global change and changes in carbon stocks. Estimating the changes in carbon stocks due to tropical deforestation has been difficult, mainly because of uncertainties in estimating deforestation rates and the biomass in the forest that have been cut. In this study, we combined detailed land-use change over a 27-year period based on satellite images and forest inventory data to estimate changes in biomass carbon stocks in the Xishuangbanna prefecture (1.9 million ha) of China. Xishuangbanna is located in southwestern China in the upper watershed of the Mekong River, and the major forest types are tropical seasonal rain forest, mountain rain forest, and subtropical evergreen broadleaf forest. In the past when the region was completely forested the total biomass carbon would have been approximately 212.65 ± 8.75 Tg C. By 1976 forest cover had been reduced to 70%, and in addition many forests had been degraded resulting in a large decrease in the total biomass carbon stocks (86.97 ± 3.70 Tg C). From 1976 to 2003, the mean deforestation rate was 13 722 ha year^{-1} (1.12%), and this resulted in the loss of 370,494 ha of forest, and by 2003 total biomass carbon stocks had been reduced to 80.85 ± 2.64 Tg C. The annual carbon emissions due to land-use change, mainly forest conversion to agriculture and rubber plantations, were 0.37 ± 0.03 Tg C year^{-1} between 1976 and 1988 and 0.13 ± 0.04 Tg C year^{-1} between 1988 and 2003. During the next 20 years, if rubber plantations expand into forests outside of reserves, shrublands, grasslands, and shifting cultivation below 1500 m the total biomass carbon stocks of Xishuangbanna will decrease to 76.45 ± 1.49 Tg C in 2023. This would reflect a loss of 4.13 ± 1.14 Tg C between 2003 and 2023, or an annual loss of 0.21 ± 0.06 Tg C year^{-1}. 1. Alternatively, if rubber plantations only expand into areas of shifting cultivation below 1500 m, and all areas presently in shrublands and grasslands are allowed to recover into secondary forests, total biomass carbon stock of the region would increase to 92.65 ± 3.80 Tg C in 2023. Under this scenario, the growth of existing forests and the expansion of new forests would result in a net sequestration of 0.60 ± 0.06 Tg C year^{-1}. This study demonstrates that the uncertainty of biomass estimates can be greatly reduced if detailed land-use analyses are combined with forest inventory data, and that slight changes in future land-use practices can have large implications for carbon fluxes.

Keywords: Land use/land cover change; Forest biomass; Carbon stocks; Future scenarios; Rubber plantations; Tropical region; Xishuangbanna

1. Introduction

As the human population continues to grow and becomes more affluent, there is an ever-increasing demand for natural resources, which is affecting the Earth's biogeochemical systems (Houghton, 1994; Ramankutty and Foley, 1999). Land use/land cover change is one of the most important factors affecting these systems, and this is exemplified by the large-scale conversion of forest to agricultural lands and pastures (Houghton, 1994; Schimel et al., 2001). Extensive deforestation and burning of forests for food production have significantly impacted the global carbon cycle by increasing rates of carbon emissions to the atmosphere and decreasing the above- and belowground carbon stocks (Houghton, 1999; DeFries et al., 2002). Globally, the long-term (1850–2000) flux of carbon from changes in land use and management released 156 PgC to the atmosphere, and the tropics were the source of approximately 60% (Houghton, 1999, 2003). During the 1980s and 1990s, the annual flux of carbon due to tropical deforestation was approximately 2.0 PgC year^{-1} (Houghton, 2003), but the uncertainties in these measurements are large (Houghton, 2005).

The major problems with estimating carbon dynamics in the tropics are poor data on rates of deforestation/reforestation and

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the actual biomass of the forests that are cut (Houghton, 2005). To improve estimates we need precise estimates of the areas of the different forest types and other land-cover types. The availability of satellite images and GIS software have greatly improved our ability to document changes even in the most remote areas of the planet (Feldpausch et al., 2006). But, an important limitation with satellite images (e.g. Landsat) is that they do not distinguish among closed forest at different stages of development. For example, the biomass of a primary tropical wet seasonal rainforest can be almost six-times greater than secondary tropical forest (Zheng et al., 2000; Tang et al., 1998); therefore, to confidently estimate regional carbon stock, it is necessary to combine land-use studies with on-the-ground forest inventory data.

The goals of this study were to understand the impact of land-use change on biomass carbon dynamics, and to explore how alternative land-use scenarios could influence future carbon budgets. Specifically, we studied land use/land cover changes for a 27-year period (1976–2003) in Xishuangbanna, China using satellite images. The land-use maps were combined with detailed forest inventory data to estimate the changes in carbon stocks. In Xishuangbanna, the conversion of tropical rain forest into rubber plantations has been one of the most important land-use changes in the region (Li et al., 2007). Given the increasing demand for natural rubber, we created alternative future scenarios that vary the development strategies for rubber plantations to determine the consequences for the regional biomass carbon stocks.

2. Material and methods

2.1. Study area

Xishuangbanna (21°08′–22°36′N, 99°56′–101°50′E), in Yunnan Province, southwest China, covers 19150 km^2, includes three counties (Jinghong, Menghai and Mengla), and borders Laos to the south and Myanmar to the southwest (Fig. 1). The region has mountain-valley topography with the Hengduan Mountains running north-south, and about 95% of the region is covered by mountains and hill. The Mekong River flows through the center of Xishuangbanna, and the region contributes more than 20 important tributaries, resulting in many river valleys and small basins (Cao and Zhang, 1997). The altitude varies from 2430 to 475 m above sea level. The climate of this region is influenced by warm-wet air masses from the Indian Ocean in summer, including monsoons, and continental air masses of subtropical origin in winter, resulting in a rainy season from May to October, and a dry season from November to April (Zhang, 1988). The annual rainfall ranges from 1100 to 2400 mm (Edit committee of Xishuangbanna Dai Autonomous Prefecture Difangzhi, 2002). The main primary forest types in Xishuangbanna are: tropical seasonal rain forest, tropical mountain rain forest, evergreen broad-leaved forest, monsoon forest over limestone, and monsoon forest on river banks (Wu et al., 1987).

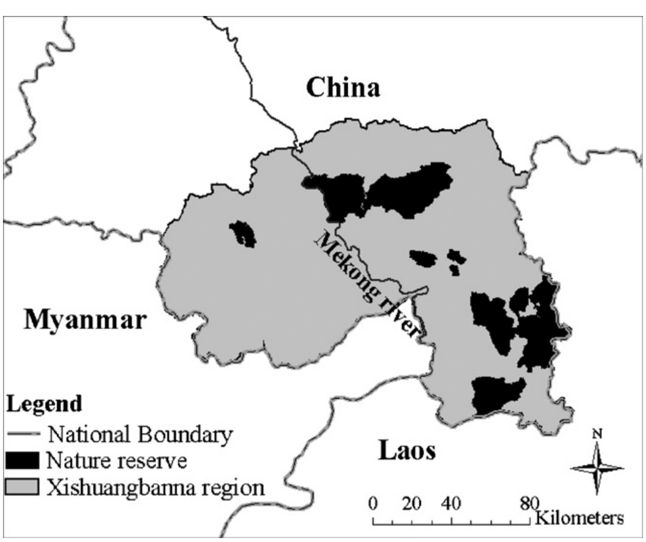

Fig. 1. The location of Xishuangbanna in the southern part of Yunnan province of China.

The combination of geography and climate in Xishuangbanna has created a transition zone between the flora and fauna of tropical South East Asia and subtropical and temperate China (Cao et al., 1996), resulting in the region with the highest biodiversity in China (Zhang and Cao, 1995; Cao and Zhang, 1997). Xishuangbanna is part of the Indo-Burma biodiversity hotspot (Myers et al., 2000). The region represents only 0.2% of the area of China, but it contains approximately 5000 species of higher plants (16% of the nation's total), 102 species of mammals (21.7%), 427 species of birds (36.2%), 98 species of amphibians and reptiles (14.6%), and 100 species of freshwater fish (2.6%) (Zhang and Cao, 1995). Although nature reserves cover approximately 12% of Xishuangbanna, rapid economic growth in China and the increasing demand for rubber has resulted in the deforestation of most of the remaining high diversity tropical seasonal rain forest in the region (Li et al., 2007).

2.2. Land use/land cover change

Land-use/land-cover change was determined using two Landsat Multi Spectral Scanner (MSS) images (24 February 1976–#139/45, and 25 April 1975–#140/45), a Landsat Thematic Mapper (TM) image (2 February 1988–#130/45) and a Landsat Enhanced Thematic Mapper (ETM) image (7 March 2003–#130/45). Two images were used to create the 1976 cover, with information from 1975 used to fill in areas with cloud cover in the 1976 image. All images were acquired during the dry season between February and April. Two land-use maps developed by the Xishuangbanna Department of Land and Resource (Xishuangbanna Land-use Status Map 1982, 1991) and a vegetation map developed by the Xishuangbanna Forestry Bureau (Xishuangbanna Vegetation Distribution Map, 1993) were used as references for the classification and accuracy estimation of the MSS and TM images, respectively. Topographic maps (scale = 1:50,000) and digital topographic data with a contour interval of 100 m published by the State Bureau of Surveying and Mapping of China were used to build a digital elevation model (DEM).

The TM satellite images were rectified to Albers Conical Equal Area projection system with a 35-m pixel size. The ETM and MSS images were registered to the TM images using an image-to-image registration technique: rectification RMS errors were <0.5 pixels and <1 pixels, respectively. All non-thermal channels of the TM and ETM images and all channels of the MSS images were used to create class spectral signatures for classification. The images were classified using the supervised maximum likelihood classification method. Training areas for each land-cover class were identified for each image. For the ETM image, training areas were identified in the field during February–March 2003. For the TM and MSS images, training areas were generated from the Department of Land and Resource maps of 1982 and 1991, and the Forestry Bureau's vegetation map of 1993, respectively. We selected large homogeneous areas for the training areas. For each land-use type, we included at least 10 training areas to reflect the variation within a land use due to topography and slope effects. Initially we used the same 15 land-use classes developed by the National Agricultural Zoning Committee (1984). Forests were classified into four classes. It was difficult to distinguish the different forest types from the images so, the common forest types Xishuangbanna (i.e. tropical seasonal rain forest, mountain rain forest and subtropical evergreen broadleaf forest) were separated based on elevation (Guo et al., 1987). Tropical seasonal rain forest is forested areas with greater than 30% closed canopy dominated by broadleaf trees, and at an altitude less than 800 m. Mountain rain forest is forested areas with greater than 30% closed canopy dominated by broadleaf trees, and at an altitude between 800 and 1000 m. Subtropical evergreen broadleaf forest is forested areas with greater than 30% closed canopy dominated by broadleaf trees, and at an altitude greater than 1000 m. Conifers and bamboos could be distinguished based on differences in texture and spectral characteristics. Rubber plantations were easy to classify because the trees are deciduous during the dry season, and most native forest species are evergreen. Shrubland is a common land-use class, but it is often a transition between abandoned agricultural land and forest or plantations. Arable lands included areas of active agriculture, shifting cultivation, grassland, tea gardens, and paddy rice. The land use polygon themes for 1976, 1988 and 2003, obtained from the digital classification of satellite date and subsequent GIS analyses were overlaid and intersected to derive land use/cover changes.

The accuracy of our classification was verified by ground-truthing. Specifically, we compared our classification of the 2003 ETM image with field observations in December 2004. A total of 286 points were verified. In each point, we determined the current land-use cover, determined the location using a global positioning system (GPS), and took a photograph of the site. The field observations were then referenced to the classification to assess the overall accuracy and the accuracy of the different land-use categories. We compared our classification of 1976, 1988 images with two land-use status maps, a vegetation map and topographic maps using 286 points of identical position in 2003. To evaluate the performance of the classification, a confusion matrix was made by comparing the classification results with the reference data based on sample identification (ground information) and some maps (Xishuangbanna Land-use Status Map in 1982, 1991; Xishuangbanna Vegetation Distribution Map in 1993; Topographic maps in 1965). The total accuracy of classification of 1976, 1988 and 2003 image was 77.3%, 86.4%, and 87.9%, respectively.

2.3. Estimating forest tree biomass

Forest biomass was calculated based on forest volume inventories and volume-biomass equations. The forest inventory, conducted in 1993–1994, sampled a broad range of forest conditions within Xishuangbanna (Anonymous, 1994a,b,c). Specifically, in each township they calculated the growing stock volume and area of each forest type, and stand size-class. At the same time, they also calculated the total forest area of each age class at the township level. Stand volume ($m^3\,ha^{-1}$) was converted to biomass ($Mg\,ha^{-1}$) using the volume-biomass equations of Pan et al. (2004):

For evergreen broadleaf forest

$y = 5.2243 + 1.1255x$	Young forest
$y = 22.967 + 1.0014x$	Intermediate forest
$y = 42.774 + 0.8436x$	Mature forest

For tropical pines

$y = 3.1299 + 0.6330x$	Young forest
$y = 6.3488 + 0.6613x$	Intermediate forest
$y = -9.1731 + 0.8127x$	Mature forest

where y is the stand biomass ($Mg\,ha^{-1}$) and x is stand growing stock ($m^3\,ha^{-1}$). These equations estimate the total above- and below-ground biomass.

We used 244 volume estimates from the forest inventory database to estimate living forest tree biomass (DBH $\geq$ 5 cm) in the different forest types, and we distinguished areas that were in reserves and areas that were outside of reserves (Table 1). Inside the reserves we were able to calculate the biomass for four forest types, tropical seasonal rain forest, mountain rain forest, subtropical evergreen broadleaf forest and conifer forest (Table 1). Outside of reserves, the forest inventory data were classified by dominant forest species, but because we knew the elevation range of each township, we selected data that occurred within the elevation range of the different forest types following the classification of forest using the method described above. No township is limited to the 800–1000 m range of mountain rain forest, so forest below 1000 m (i.e. tropical seasonal rain forest and mountain rain forest) were combined into a single forest class, tropical rain forest (Table 1). Inventory data above 1000 m were used to estimate the subtropical evergreen broadleaf forest biomass. Conifer forests are usually monospecific (e.g. *Pinus kesiya* Royle es Gorden); therefore we selected inventory data based on the dominant species.

To calculate the regional biomass or carbon stocks we multiplied the total area of each forest type in 1976, 1988 and 2003 by the mean stand biomass of the forest type. Biomass was assumed to be 50% carbon. Although the land-use analyses based on the satellite image could not distinguish among forest

Table 1
Estimates of forest biomass carbon density in Xishuangbanna based on forest inventory data and other vegetation biomass carbon

Land use/land cover	*N*	Mean biomass carbon density (Mg C ha^{-1} ± S.E.)	Reference
Forest type (elevation range)			
Inside nature reserve (mature forest)			
Tropical seasonal rain forest (<800 m)	4	121.74 ± 6.99	
Mountain rain forest (800–1000 m)	3	116.24 ± 3.83	
Subtropical evergreen broadleaf forest (>1000 m)	5	105.24 ± 3.99	
Conifer forest	1	31.54	
Outside nature reserves			
Tropical seasonal rain forest and mountain rain forest			
Young	26	29.23 ± 3.05	
Intermediate	24	56.06 ± 3.75	
Mature	28	75.17 ± 4.18	
Mean carbon density		49.84 ± 3.13	
Subtropical evergreen broadleaf forest			
Young	27	32.15 ± 2.64	
Intermediate	36	54.73 ± 1.89	
Mature	59	71.00 ± 3.04	
Mean carbon density		53.22 ± 2.13	
Conifer forest			
Young	11	28.39 ± 3.03	
Intermediate	8	36.85 ± 3.46	
Mature	12	51.44 ± 5.00	
Mean carbon density		37.19 ± 2.77	
Rubber plantation (elevation range)			
<800 m		61.48	Xie (1989); Jia (2006)
800–1000 m		35.09	Xie (1989); Jia (2006)
>1000 m		15.31	Xie (1989); Jia (2006)
		30.47	Guo et al. (1987)
Bamboo			
Shrublands		14.56	Hu et al. (2006)
Grasslands		5.32	Hu and Guang (2000)
Tea garden		14.26	Xie (1989)
Shifting cultivation		3.81	Li (2002)
Paddy		5.41	Li (2002)

stand of different age, we assumed that forest outside of the reserve were a mix of young, intermediate and mature forests and we applied the mean biomass of these three age classes within each forest type (Table 1). In our study, the selected sample area outside of nature reserves for estimation of stand biomass was about 21% of total forest area in Xishuangbanna in 1994, where forests across heterogeneous regions could, on average, experience very different growth conditions. There are common age classes for the age groups of forests in Yunanna (Xue and Jiang, 1986). For coniferous species, the young forest age is less than 20 years, intermediate forest age is between 21 and 40 years, and mature forest is ≥41 years. For hardwood forest, the young forest age is less than 40 years, intermediate forest age is between 41 and 80 years, and mature forest is ≥81 years. For other broad leaf forest, the young forest age is less than 20 years, intermediate forest age is between 21 and 50 years, and mature forest is ≥51 years. For softwood forest, the young forest age is less than 10 years, intermediate forest age is between 11 and 20 years, and mature forest is ≥21 years.

Biomass of rubber plantation, shrubland, tea, grassland, and irrigate field/paddy field were taken from the literature (Table 1). In this study, we did not include soil carbon, and a biomass value of 0 was assigned to areas classified as water, sandy, or urban.

2.4. Historical and future scenarios of carbon stocks

As a point of reference, we calculated the historical carbon stocks assuming that Xishuangbanna was completely covered by mature forests of tropical seasonal rain forest, mountain rain forest and subtropical evergreen broadleaf forest. This assumption was based on the local climatic conditions, which permit the formation of tropical vegetation. First, the Hengduan Mountains form a barrier to cold air entering Xishuangbanna from the north during the winter. Second, the montane topography produces dense fog during the dry season, which supplements the low precipitation and facilitates forest growth (Zhu, 2006). In addition, historically, the human population of Xishuangbanna was low because of poor access, and thus deforestation would have been limited. We also assumed that each forest type would have a distribution with the same limits used in the present study, and that the biomass would be the same as the estimates of the mature forests within the reserves (Table 1).

Two future scenarios of land use/land cover change beginning in 2003 were developed for Xishuangbanna. In Scenario 1, the rubber expansion scenario, we assumed that the increasing demand for rubber will continue and this will be an important driver of rubber plantation expansion in Xishuangbanna during the next 20 years. Presently, most of rubber plantations occur below 1000 m, but some authors suggest that in the Xishuangbanna region rubber trees could be productive up to approximately 1500 m (Jiang, 1982; Wang et al., 1991). In this scenario, we assumed that forests, shrublands, grasslands, and shifting cultivation that occur below 1500 m and outside of nature reserves would be converted to rubber plantations. Urban area was assumed to grow at the same rate calculated between 1988 and 2003. New urban areas will come from areas that are presently in paddy rice, but the remaining area of paddy rice will remain in this land-use. We also assumed that because shifting cultivation below 1500 m would be transformed into rubber plantation, all areas of shrublands and grassland above 1500 m would be converted to agriculture lands. Forest area above 1500 m or within reserves will not change, but non-forest land uses presently within nature reserve will convert to forest by 2023.

In Scenario 2, the forest recovery scenario, we assume that new land-use policies will limit the expansion of rubber plantation and encourage forest conservation and forest recovery. In this scenario, rubber plantations are permitted to expand into areas of shifting cultivation below 1500 m. Shifting cultivation above 1500 m would continue in this land use. In this scenario, all shrublands and grasslands would be allowed to recover into secondary forests and they would have the biomass equivalent of a young forest in 2023. The change in urban areas, paddy rice, and nature reserves would be same as described in scenario 1. In scenario 2, we assumed that the food supply for the region would depend on a combination of imported food and an increase in productivity on exiting agricultural lands through intensification and improved management.

3. Results

3.1. Land cover change

Historically, the Xishuangbanna region would have had close to 100% forest cover, dominated by tropical seasonal rain forest (21%), mountain rain forest (23%), and subtropical evergreen broadleaf forest (57%) (Figs. 2 and 3). By 1976, forest cover had been reduced to 70% and by 2003 to 50%. During the period 1976–2003, forest area was reduced by about 370,494 ha, or 28%, and the mean annual deforestation rate was 13 722 ha $year^{-1}$, or 1.12%. This deforestation disproportionately affected tropical seasonal rain forest, which lost 139 576 ha (67%) and by 2003 only covered 4% of the area.

These forested areas have mainly been replaced by rubber plantations, shrublands, and shifting cultivation. Between 1976 and 2003, the area in rubber plantations increased by 194 151 ha (gain of 90%), and the area of shrublands increased by 129,581 ha (gain of 37%) (Figs. 2 and 3). Shifting cultivation lands increased by 75,419 ha between 1976 and 1988, and then decreased by 66,648 ha between 1988 and 2003. The area in tea garden and grasslands increased slightly, and there was little change in the other land uses during the 27-year period (Figs. 2 and 3).

If the assumptions of the rubber expansion scenario are met, by 2023, the total forest cover will decrease to 24%, and the area of tropical seasonal rain forest, mountain rain forest and subtropical evergreen broadleaf forest will be reduced to 1%, 5% and 18%, respectively. In contrast, if the forest recovery

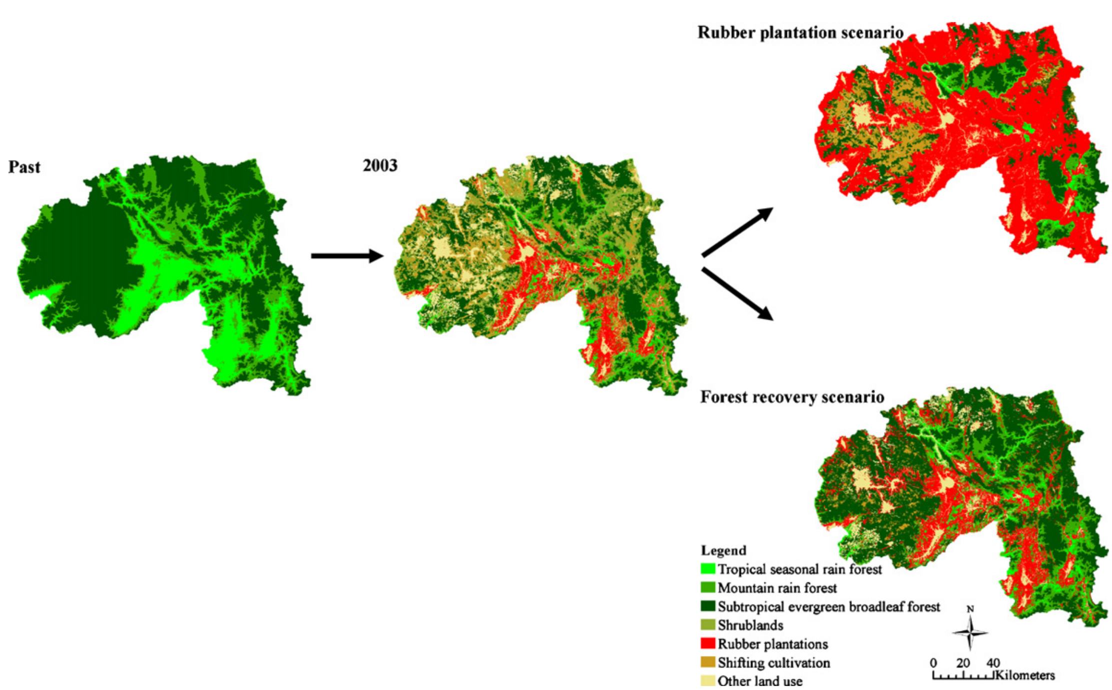

Fig. 2. Land use/land cover in the past, 2003, and for two future scenarios. (Other land use including conifer forest, bamboo forest, grasslands, tea garden, paddy field, irrigable field, water, sand and urban area.)

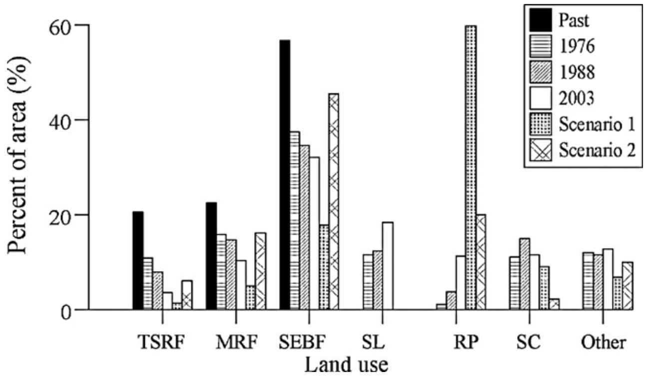

Fig. 3. The percent of area of different land use in the past, 1976, 1988, 2003 and for two future scenarios in Xishuangbanna. (TSRF: tropical seasonal rain forest; MRF: mountain rain forest; SEBF: subtropical evergreen broadleaf forest; SL: shrublands; RP: rubble plantations; SC: shifting cultivation; other: other land use including conifer forest, bamboo forest, grasslands, tea garden, paddy field, irrigable field, water, sand and urban area.)

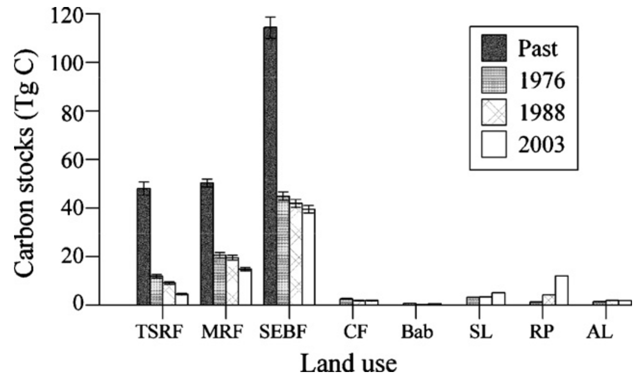

Fig. 4. Change in biomass carbon stocks through time (past, 1976, 1988, and 2003) for the different land–use/land-cover categories. (TSRF: tropical seasonal rain forest; MRF: mountain rain forest; SEBF: subtropical evergreen broadleaf forest; CF: conifer forest; Bab: bamboo; RP: rubble plantations; SL: shrublands; Al: arable lands including shifting cultivation, tea garden, paddy field, irrigable field.)

scenario reflects the future, then forest cover will increase to 72% (Figs. 2 and 3).

3.2. Biomass carbon stocks dynamics

Inside the nature reserves, forest biomass carbon ranged from 31.54 Mg C ha^{-1} (mean $\pm$ S.E.) in conifer forest to 121.74 $\pm$ 6.99 Mg C ha^{-1} in tropical seasonal rain forests (Table 1). Forest biomass carbon outside of the reserves ranged from 37.19 $\pm$ 2.77 Mg C ha^{-1} in conifer forest to 53.23 $\pm$ 2.13 Mg C ha^{-1} in subtropical evergreen broadleaf forest. These lower forest biomass carbon values reflect the higher disturbance rates and larger areas of young and middle age forest stands. In 1994, most of the forest stands outside of the reserves were of intermediate aged forest (56%), followed by young forest (32%), and mature forests (12%). The average biomass carbon was highest in mature forests (69.64 $\pm$ 2.42 Mg C ha^{-1}) followed by intermediate (52.95 $\pm$ 1.80 Mg C ha^{-1}), and young forest (30.31 $\pm$ 1.73 Mg C ha^{-1}).

In the past when the region was completely forested the total biomass carbon would have been approximately 212.65 $\pm$ 8.75 Tg C (Figs. 4 and 5). By 1976 the total biomass carbon stocks for all land-use/cover types in Xishuangbanna decreased to 86.97 $\pm$ 3.70 Tg C, and by 2003 it was 80.58 $\pm$ 2.64 Tg C (Figs. 4 and 5). The annual carbon emissions rate was 0.37 $\pm$ 0.03 Tg C year^{-1} between 1976 and 1988, and 0.13 $\pm$ 0.04 Tg C year^{-1} between 1988 and 2003.

The largest carbon stocks have always been in the forests, particularly in subtropical evergreen broadleaf forest (Fig. 4). Historically, when the human population density was low and forest disturbance was limited, total forest biomass carbon stock was 212.65 $\pm$ 8.75 Tg C, and more than 50% occurred in subtropical evergreen broadleaf forest (114.35 $\pm$ 4.34 Tg C). Conversion of these forests to other uses has greatly reduced these carbon stocks (Fig. 5). From the past to 2003, tropical seasonal rain forest biomass carbon stocks decreased from 48.00 $\pm$ 2.76 to 4.55 $\pm$ 0.28 Tg C and mountain rain forest carbon stocks decreased from 50.29 $\pm$ 1.66 to 14.85 $\pm$ 0.67 Tg C. In 2003, subtropical evergreen broadleaf forest maintains the largest biomass carbon stocks (39.54 $\pm$ 1.55 Tg C), but this reflects a loss of 74.81 $\pm$ 2.78 Tg C from past times.

The expansion in rubber plantations, particularly in areas that were covered by tropical seasonal rain forest, has become another significant carbon stocks. Between 1976 and 2003 the biomass carbon stocks in all rubber plantations increased from 1.33 to 12.11 Tg C in 2003. The importance of other land-use categories is limited because they are characterized by low biomass carbon or they do not cover extensive areas.

Slight changes in future management or land-use policy decisions could make very large differences in future biomass carbon stocks (Fig. 5). If rubber plantation are permitted to expand up to 1500 m, i.e. rubber expansion scenario, the total biomass carbon stocks of Xishuangbanna will decrease to 76.45 $\pm$ 1.49 Tg C in 2023. This would reflect a loss of 4.13 $\pm$ 1.14 Tg C between 2003 and 2023, or an annual loss of 0.21 $\pm$ 0.06 Tg C year^{-1}. In the forest recovery scenario, rubber plantations are permitted to expand into the 170,417 ha of shifting cultivation that occurs below 1500 m, and all shrublands and grasslands will be allowed to recover through natural regeneration. The consequences of this scenario would be an increase of 12.07 $\pm$ 1.17 Tg C over the 2003–2023

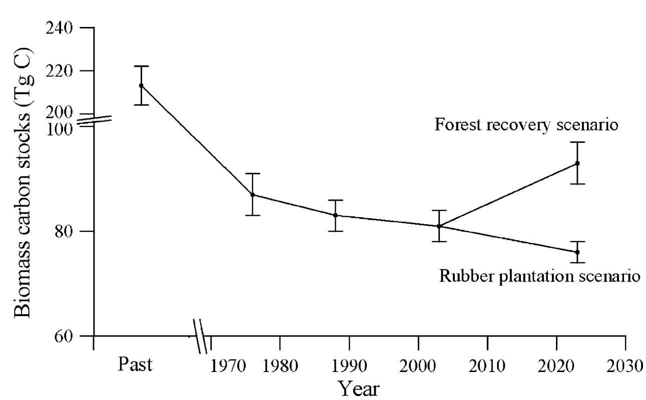

Fig. 5. Biomass carbon stocks in the past, 1976, 1988, 2003 and two future scenarios.

period, which would increase to total biomass carbon stock of the region to 92.65 ± 3.80 Tg C. The growth of existing forests and the expansion of new forests would results in an average net sequestration of 0.60 ± 0.06 Tg C year^{-1}.

4. Discussion

4.1. Forest biomass carbon stock

In this study we combined detailed GIS analyses of land use and land cover with forest inventory data and volume-biomass methods to estimate changes in biomass carbon stocks. Our estimates inside the nature reserves were similar to estimates of other relatively undisturbed forests in Xishuangbanna. For example, our estimate of biomass carbon in tropical seasonal rain forest (122 Mg C ha^{-1}) was very similar to Lu et al. (2006) who estimate biomass carbon (128 Mg C ha^{-1}) by measuring all individuals with a DBH greater than 2.0 cm in 1 ha permanent plot and using allometric regressions. Similarly, our estimate of biomass carbon of evergreen broadleaf forest (105 Mg C ha^{-1}) was in the range of values measured by Li (2006) (102–159 Mg C ha^{-1}). In tropical Asia (including Pakistan, India, Bangladesh, Sri Lanka, Burma, Thailand, Cambodia, Laos, Vietnam, Malaysia, Singapore, Brunei, Indonesia, Papua New Guinea, and the Philippines) Houghton and Hackler (1999) estimated a range of biomass carbon from 46 Mg C ha^{-1} in dry forest, to 120 Mg C ha^{-1} in seasonal forest, and 196 Mg C ha^{-1} in moist forest in 1995. The slightly lower estimates in our sites may reflect some selective logging activities even within the reserves, but an alternative explanation is that the tropical rain forest in our study is near its northern limit. The lower diversity and importance of ‘‘true’’ lowland tree species could reduce the overall productivity of these forests (Zhu, 1997).

But, the most striking results were the much lower carbon stocks (the average value of 50 Mg C ha^{-1}) in forest stand outside the nature reserves. The landscape in this region is a mosaic of secondary forests and forests that have been selectively logged, resulting in lower and highly variable levels of biomass carbon. These differences are difficult to detect from satellite images, and this is why the forest inventory data was an important part of these estimates. If we had used the nature reserves estimates for the whole region we would have greatly overestimated carbon stocks. Furthermore, the forest inventory data allowed us to sample many sites (the sample area outside nature reserves was approximately 21% of the total forest area), and this helped to document the variation among forest stands that often varied greatly in age.

It is difficult to make accurate estimates of forest biomass or carbon stocks because there are many uncertainties, but a few methodological changes could greatly help to reduce the uncertainties and improve regional estimates of carbon stocks. Two of the largest problems are incorporating the natural variation that exists among stands across a large area and converting diameter and height measurements into biomass. Minimizing the uncertainty of estimation forest biomass at the regional or global scales will require greatly increasing the number and area of long-term plots where repeated surveys and standardized methodology can better reflect the biomass change and the possible causes (Chave et al., 2003). But, to capture the variation that exist in most regions it will not be sufficient to only establish plots in protected areas. As we have shown, forest biomass can vary greatly and it is important to capture the effects of degradation outside of protected areas and recovering forest stands of different age. In Xishuangbanna, we were able to improve biomass carbon estimates by combining remote sensing data with a forest inventory, but in areas where forest inventory data are not available lidar remote sensing can accurately measure the height and vertical structure of a forest (Saatchi et al., 2001; Drake et al., 2003).

Even when many plots have been sampled, or remote sensing provides forest structure data, converting these data into biomass is still the largest limitation (Barrett et al., 2001) because the use of different biomass algorithms can results in large difference in estimates of carbon stock (Fang et al., 1998, 2001a; Fang and Wang, 2001b; Pan et al., 2004). Fang et al. (1998) used three methods (i.e. biomass–volume relationship, mean biomass density, and mean ratio of biomass to stem volume) for estimating forest biomass of China, and they found a 80% difference between the lowest and highest estimates. Similarly, there was a two-fold difference in biomass estimate of the same tropical wet seasonal rain site in Xishuangbanna between studies that used different biomass algorithms (Feng et al., 1998; Zheng et al., 2000). To reduce this problem, we used biomass algorithms that were developed for each age class of the major forest types (Pan et al., 2004).

Another important uncertainty we did not include was soil organic carbon stocks, and these stocks are strongly influenced by land-use and land-cover change. For example, six years after secondary forest were converted to cropland, soil organic carbon decreased by 33.6% and 23.7% at depths of 0–5 cm and 5–20 cm, respectively (Yang et al., 2004). Similarly, the conversion of secondary forests to rubber tree plantations also reduced soil organic matter by approximately 18% (Yang et al., 2004). Given that the major land-use changes in the region have been the conversion of forest to rubber plantations and shifting cultivation, if soil carbon loss had been included, our estimates of carbon emissions would be even larger than we reported.

4.2. Potential for increasing biomass carbon storage

The major factor affecting the carbon dynamics in Xishuangbanna between 1976 and 2003 has been the conversion of large area of forest to shifting cultivation and rubber plantations (Figs. 2 and 3). Although extensive deforestation occurred prior to 1976 (Figs. 2–5), the increasing demand for natural rubber, and a series of national policies, such as the *Household Responsibility System Policy* in 1979 (Xu et al., 1999), *Natural Forest Conservation Program* in 1998 (Long et al., 1999), and *Sloping Land Conversion Program* in 1999 (Zhang et al., 2000), have directly or indirectly promoted the expansion of rubber plantations, which has virtually replaced tropical seasonal rain forest (Fig. 2). Rubber plantation have also been established in areas of shifting cultivation, and this reduced the rate of carbon emissions between 1988 and 2003, but the continued loss of forest is the major factor affecting carbon dynamics.

The increasing demand and high price of natural rubber will most likely lead to a continued expansion of rubber plantations in Xishuangbanna. Thus, the important questions are how much area should be dedicated to rubber plantations and where will they be established. From the perspective of carbon storage/sequestration and biodiversity we showed that it is possible to increase carbon stocks and permit rubber plantations expansion (forest recovery scenario). If rubber plantations were established in areas of shifting cultivation below 1500 m (170,417 ha) this would help to meet the increasing demand for natural rubber, and at the same time increase carbon stocks. But, even larger carbon gains could be made if grassland and shrublands were allowed to recover into forests (Hashimotio et al., 2000). For example, aboveground biomass increased at a rate of >6 Mg ha^{-1} during the first five years of secondary succession following the abandonment of slash and burn agriculture in Xishuangbanna (Shi et al., 2001). Furthermore, if the considerable area that is occupied by young aged stands in Xishuangbanna is allowed to grow they will be important regions of carbon sequestration for the next 40–80 years.

Further gains in carbon sequestration could be achieved by promoting agroforestry activities as an alternative technology to slash-and-burn farming. A diversity of agroforestry models have been tested in Xishuangbanna (Chen, 1991), and one of the most successful has been the establishment of tea in the understory of rubber plantations (Xie, 1989). In addition to increasing carbon storage, the system will reduce soil erosion and diversify the farmer's production.

The opportunities for carbon gains exist. An important first step is to improve the quantification of carbon dynamics by expanding the area sampled within a region and incorporating biomass equations that are appropriate for the local flora. Second, simple scenario modeling (e.g. Jiang et al., 2002; Grau et al., 2004; KimPhat et al., 2004) can provide realistic alternatives that can be incorporated into regional land-use management plans to improve our management of terrestrial carbon pools and fluxes, especially for the long-term sustainable use and management of tropical forests.

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