CHAPTER 5

DISCUSSION

The inhabitants of the Naban River Watershed National Nature Reserve mostly rely on agriculture for their livelihoods, including e.g. rice, orchards, tea, maize, and rubber. Nevertheless, the area does not offer optimal requirements for rubber cultivation regarding average annual temperatures at ME and HE, rainfall, atmospheric humidity during the dry season, and elevation (Chapter Three and Four). Among these suboptimal conditions, especially lower temperatures lead to an overall lower rubber biomass accumulation compared to traditional rubber cultivation areas (Chapter Five), and results in lower latex yields (Jia, 2006). Despite the unfavourable conditions for rubber cultivation, 10% of the NRWNNR is covered with rubber plantations, which offer an important additional annual income of up to €3,581 per ha to rubber farmers (Cotter, 2011).

The fast rubber expansion rate in Xishuangbanna may be explained by its attractive income opportunity, as well as by the Chinese Government's efforts to promote rubber cultivation (Fox et al., 2009), and the overall tendency of world natural rubber prices to increase (FAOSTAT and Index Mundi). Nonetheless, rubber plantations mainly replace forests (Chapter Six), leading to major changes in carbon sequestration and emissions in the NRWNNR. Therefore, this study used an extensive literature review to parameterize the LUCIA model, as well as for evaluating the biomass accumulation of the area's primary and secondary forest types, of rubber plantations at different elevation ranges and of other agricultural land uses. Field data (Golbon, 2012, personal communication) and published data are used for the development of allometric equations to estimate rubber biomass at the reserve's different elevation ranges. This thesis also assesses the resulting carbon balance of the selected sub-watershed during the simulation period - between 1992 and 2003 - with the help of the model Land Use Change Impact Assessment. For this purpose, it was necessary to create past land use maps of the sub-watershed for 1992 until 2003, and to assess the model's simulation outputs that comprise biomass carbon, litter inputs, exported carbon, soil carbon and soil CO_2 emissions of rubber, primary and secondary forests, maize, paddy rice, orchards/tea, and grasslands.

Rubber and Forest Biomass

Biomass accumulation per ha in rubber plantations significantly differs between the three elevation ranges. It decreases in the following order: LE > ME > HE, which can be mainly explained by the reduction of temperature as elevation increases (Chapter Five), thereby confirming the author's hypothesis (Chapter One). Lower temperatures have a tendency to restrict rubber biomass development, so that even flowering and consequently fruiting are not possible at HE. Additionally, a lower biomass also implies a lower latex production (Chapter Five, Jia, 2006), which confirms the author's hypothesis (Chapter One). Furthermore, the biomass accumulation in different plant organs is generally higher at LE > ME > HE. However, an exception was observed in branch and leaf biomasses, which were higher at ME than at LE. This can be partially explained by the biomass allocation at ME, which compared to LE is greater to branches and leaves, and simultaneously lower to stems (Chapter Five). It can also be partly explained by the winter temperature inversion in the area, which occurs over 80% of the days between the beginning of December and the end of February (Jiang, 1981). This may influence the greater branch and leaf biomass development at ME, where the beginning of leaf growth occurs around the 10^{th} of February, i.e. already about 9 days earlier than at LE (Jia, 2006). Nevertheless, there is no frequent temperature inversion during the rest of the year (Jiang, 1981), which then explains the significantly higher stem biomass accumulation at LE compared to ME and HE.

The biomass accumulation in the area's forests, in descending order, is highest in primary seasonal tropical rainforests, followed by primary subtropical evergreen broadleaf forests, primary tropical montane rainforests, mature secondary evergreen broadleaf forests, and mature secondary seasonal and montane rainforests (Chapter Five). This agrees with the author's hypothesis that mature secondary forests have less biomass than primary forests. The biomasses of primary tropical montane rainforests and of rubber at LE only differ by 0.65 t per ha, and are averages taken from different rubber plantations at LE and primary tropical montane rainforests in the area. Therefore, it is likely that depending on the specific sampling area, either rubber at LE or primary tropical montane rainforests will have a higher biomass accumulation.

The biomass accumulation of non-simulated and all simulated land uses in the area, in descending order, is highest in primary tropical seasonal rainforests, followed by primary evergreen broadleaf forests, rubber at LE or primary montane rainforests, rubber at ME, secondary evergreen broadleaf forests, secondary seasonal and montane rainforests, rubber at HE, grasslands, orchards/tea, maize, and finally paddy rice. This agrees with the author's hypothesis and literature data for regions with similar climatic conditions stating that primary forest types in the area have a higher biomass carbon accumulation than any other land use, and that mature secondary forests can sequester more biomass carbon than orchards/tea, maize and paddy rice fields (Chapter Five; Li et al. 2008; Li et al., 2006; Lu et al., 2006; Zheng et al., 2006; Lü et al., 2009; Feng et al., 1998 and Bao et al., 2008).

Furthermore, rubber has a 38 year life cycle, in which it is unable to compensate the biomass carbon loss when replacing primary tropical seasonal rainforests or primary subtropical evergreen broadleaf forests in the study area. Rubber at LE has a similar biomass than primary tropical montane rainforests (normally at ME, HE or above). If they were located at the same elevation range, than rubber at LE could compensate the biomass carbon loss of replacing primary tropical montane rainforests in its 38th year after plantation.

Nonetheless, already 18 up to 21 years after rubber is planted at LE and ME, it is able to compensate the biomass carbon loss of replacing a mature secondary tropical seasonal and montane rainforest, and a mature secondary subtropical evergreen broadleaf forest, respectively. Therefore, rubber plantations at LE and ME in the middle of their life cycle are able to surpass the biomass carbon sequestration capacity of mature secondary forests, contradicting the author's hypothesis that secondary forests store more biomass carbon than mature rubber plantations. Only rubber plantations at HE cannot compensate for the biomass carbon loss of replacing neither primary nor secondary forests, which confirms the author's hypothesis for this case.

Simulated Biomass, Soil Carbon, Soil CO_2 Emissions and Carbon Balance

The areas of the simulated land uses in the sub-watershed in 2003, in descending order, are larger for secondary forests, followed by primary forests, rubber, maize, paddy rice, grasslands, villages, tea, and orchards. Between 1992 and 2003, land use change in the sub-watershed was mainly driven by the expansion of rubber, maize and paddy rice plantations that together increased by an average of 131.1 ha per year. This largely implied the simultaneous reduction of secondary forests by an average of 130.1 ha per year, and to some extent that of primary forests by an average of 1.9 ha per year. For the entire simulation period, this means a reduction of 1.1% for primary forests and of 31.0% for secondary forests. Furthermore, tea plantations increased by an average rate of only 1.2 ha per year, while the areas under grasslands, villages and orchards did not change by more than 1.0 ha throughout the entire period.

Moreover, the rubber expansion rate dropped from an average of 128.5 ha per year until 1997 to 19.8 ha per year from 2000 onwards. Additionally, the rice expansion rate is reduced from an average of 52.8 ha per year until 1996 to 1.5 ha per year from 1998 onwards. Tea and orchards did not expand since 1997. At the same time, the contraction rate of secondary forests decreased from an average of 176.8 ha per year until 1999 to 48.4 ha per year from 2000 until 2003. Furthermore, maize kept expanding at a similar rate throughout the entire simulation period. Accurate information on the real land use change rates of the different land uses in the sub-watershed between 1992 and 2003 could not be accessed. The land use change rates in this study are a consequence of the selected model scenario, and have a land use change rate pattern comparable to that of the NRWNNR between 1994 and 2004 (Wehner, 2010, p. 14).

Biomass

The biomass per ha of the watershed's land uses, in descending order, is highest in primary forests, secondary forests, 11 year old rubber plantations at LME, 11 year old rubber plantations at HE, grasslands, orchards/tea plantations, maize plantations at LMHE, and paddy rice plantations at LMHE. With the highest biomasses per ha, primary and secondary forests are the most important contributors to biomass carbon sequestration per ha in the watershed. Furthermore, the lower biomasses of orchards/tea, grasslands and rubber reduce their importance as biomass carbon stocks compared to forests. Nevertheless, older rubber plantations (not simulated in this study) can surpass secondary forest biomass, thereby increasing their value as carbon stocks. Paddy rice and maize plantations are only seasonally able to store carbon in their relatively low biomasses, which makes their contribution to carbon sequestration unimportant in the long-term. As a result, biomass carbon storage is more important in perennials.

The biomasses by land use area, except that of secondary forests, increase throughout the simulation period. Such increases can be mainly attributed to the expansion of rubber, maize, paddy rice, tea and orchards, the unchanged size of grasslands, and the small contraction of primary forests. The biomass reduction of secondary forests mostly results from their replacement with plantations of rubber, maize, and paddy rice. Primary forests are replaced to a lower extent, but the increase of their biomass per ha throughout the simulation explains the increasing primary forest biomass of the watershed. Furthermore, grasslands remain the same size, but their biomass per ha increases as well.

Secondary forests represent the watershed's largest biomass carbon stocks until 1999. Despite covering the largest area of the watershed throughout the simulation period (46.2% in 2003), they represent the second largest stocks from 2000 onwards. Primary forests cover 27.3% of the study area in 2003, and represent the second largest carbon stocks until they surpass secondary forest stocks in 2000 and start having the largest stocks. This can be attributed to the larger biomass per ha of primary forests and the reduction of secondary forest area.

With a biomass of 496,672.41 Mg in primary forests and of 464,527.79 Mg in secondary forests in 2003, they are the watershed's most important carbon stocks. With 42,599.60 Mg in 2003, rubber has a much lower biomass than forests, and is simultaneously the third largest land use (12.4%) and biomass carbon storage. Maize is the fourth and paddy rice is the fifth largest land use, covering 5.4% and 5.1% of the area, respectively. However, their contribution to biomass carbon sequestration is only seasonal, and therefore not important in that regard. Grasslands, tea and orchards cover 2.8%, 0.2% and 0.03% of the watershed, respectively, and simultaneously represent the lowest biomass carbon stocks among the perennials.

The watershed's biomass carbon stocks decrease yearly until 2000, which results from the strong reduction of secondary forest biomass due to deforestation. However, it stabilizes from 2000 until the end of the simulation period. This is possibly due to the rapidly increasing biomass of the rubber plantations, and the coinciding reductions of paddy rice and rubber expansion rates that start in 1998 and 2000, respectively.

Soil Carbon

Overall, the topsoil carbon content per ha, in descending order, is higher under maize, primary forests, secondary forests, grasslands, paddy rice, orchards/tea, and finally rubber. The topsoil carbon per ha of all land uses, except maize and paddy rice, in the watershed decreases notably throughout the simulation period. However, as the soil erosion of most land uses is negligible, it is not likely that erosion accounts for the high carbon reductions in topsoil. Paddy rice, maize and rubber have visibly higher soil erosion amounts. Nevertheless, topsoil carbon under rubber shows no distinct pattern compared to land uses with negligible erosion. Maize has the highest erosion, but its topsoil carbon decreases by only 2.95 Mg C per ha between 1992 and 2003, while that of other land uses decreases by between 10.03 and 26.38 Mg C per ha. Moreover, the topsoil carbon of paddy rice increases throughout the simulation period. Therefore, it is unlikely that erosion has an important influence on the topsoil carbon of any land use in the watershed. This holds true at least for the current set of model parameters, where soil organic matter mineralization is more important for soil carbon losses in the long-term (see section Soil CO_2 Emissions).

As paddy rice and maize fields are not fertilized with manure, it makes no direct contribution to topsoil carbon. If manure from neighbouring rubber or orchards/tea fields reaches paddy rice and maize fields, it is nevertheless unlikely that it has an important influence on their topsoil carbon, as it already shows no important influence on the topsoil carbon of rubber and orchards/tea. Moreover, topsoil carbon per ha in paddy rice and maize increases after every harvest, then it decreases, returning to about its level before harvest. This suggests a strong influence of litter inputs and exported carbon on topsoil carbon. The cumulative litter amounts per ha of paddy rice and maize are at least 100 times higher than in any other land use in the watershed. This results from the LUCIA model's underestimation of litter inputs for perennials. Furthermore, paddy rice litter surpasses exported carbon, explaining its topsoil carbon increase throughout the simulation period. Maize litter is only slightly surpassed by exported carbon, which can explain the only slight decrease of topsoil carbon.

Land uses with perennials have a carbon exports per ha that are higher than litter inputs, resulting in a decrease of soil organic carbon stock. Another reason for soil carbon stock decrease is the mineralization of soil organic carbon (see section Soil CO_2 Emissions). This may explain the topsoil carbon reduction of grasslands, forests, rubber and orchards/tea throughout the simulation period. Additionally, grasslands, forests, rubber and orchards/tea have similar litter amounts. Nevertheless, forests and grasslands have more topsoil carbon, while rubber and orchards/tea have notably less. On one hand, this can be partially explained by the soil organic carbon (SOC) content of 4.28% of Ferralsols underlying forests and grasslands, the SOC of 3.17% of Acrisols under rubber, and the SOC of 1.81% of Acrisols under orchards/tea. On the other hand, it can be partly attributed to the higher carbon exports of orchards/tea and rubber throughout the simulation period, which reach 12.26 and 9.65 Mg C per ha, respectively, while primary forests follow with only 3.62 Mg C per ha. Finally, as soil erosion and carbon input from manure do not show an important influence on topsoil carbon, it is possible that the topsoil carbon of every land use in the watershed is largely defined by mineralization rate of soil organic carbon.

Moreover, the subsoil carbon content per ha of most land uses is similar and decreases throughout the simulation period. However, paddy rice is the only land use that despite this reduction shows an evidently higher subsoil carbon content. This may be attributed to a combination of its SOC of 1.08% in subsoil (Gleysols) and it being the only land use that has much higher litter inputs than exported carbon, thereby having a positive effect on carbon balance. The litter inputs of maize are only slightly higher than its carbon exports, while the SOC in its subsoil is lower than that of paddy rice with 0.8%.

The total soil carbon per ha of all land uses, including paddy rice, decreases throughout the simulation period. As a result, the total soil carbon of the land use areas that contract or remain about the same size also decreases, e.g. in secondary forests, primary forests, and grasslands. However, when land use area expands rapidly in the beginning and slows down later, the total soil carbon tends to increase for a part of the simulation period before it begins to drop around 1996 for orchards, in 1998 for paddy rice and tea, and in 2002 for rubber. Furthermore, the total soil carbon of the area under maize increases throughout the simulation period, which can be explained by its constant expansion rate, and its litter inputs that are slightly higher than its carbon exports.

Despite the large reduction of secondary forests, they account for the largest soil carbon stocks throughout the simulation period, followed by primary forests. Total soil carbon under rubber plantations in the watershed start to increase from 0 in 1992, and it represents the third largest soil carbon sink by 2003. Moreover, the soil carbon stocks of rubber do not even account for half of those of primary forests in 2003. However, they are over 34.2% and 48.3% higher than maize and paddy rice stocks, respectively, which represent the watershed's fourth and fifth largest stocks. In descending order, grasslands, tea and orchards represent the remaining soil carbon stocks. Furthermore, the reduction of the watershed's total soil carbon over the simulation period can be mainly attributed to the also decreasing total soil carbon per ha of all land uses.

Soil CO_2 Emissions

Soil CO_2 emissions of all vegetation types are lower during the dry season in Xishuangbanna, and are higher throughout the rainy season, as confirmed for forests by Werner et al. (2006). Moreover, maize and paddy rice present a sharp peak of CO_2 emissions every year after they are harvested. This can result from the decomposition of litter that is left after their harvest and contribute to temporarily strongly increase CO_2 releases.

The CO_2 emissions per ha of all land uses in 2003, in descending order, are highest in primary forests, followed by secondary forests, orchards/tea, paddy rice, grasslands, rubber at LME, and rubber at HE. The emissions of all land uses, except those of rubber at LME, decrease over the simulation period. This can be explained by the total soil carbon decrease of all land uses. However, rubber and orchards/tea have a similar total soil carbon; therefore, the higher emissions from orchards/tea can be explained by the higher litter input and its consequent high decomposition. Therefore, the much lower litter inputs of rubber may cause rubber at LME and rubber at HE to have the lowest CO_2 emissions among all land uses in the watershed. In order to confirm this conclusion, the default model parameterization for litter production in rubber plantations needs to be further refined based on experimental observations. The emissions of the other land uses are between 22.0% and 171.7% higher. Nevertheless, the simulated rubber plantations have a maximum age of 11 years; therefore, it can be expected that CO_2 releases will increase as biomass continues accumulating and litter inputs increase over the years.

The CO_2 emissions by land use area in 2003, in descending order, are highest in secondary forests, followed by primary forests, maize, rubber, paddy rice, grasslands, tea, and orchards. The areas under rubber and maize plantations present yearly CO_2 emission increases as they expand. The emissions of the areas under paddy rice, tea and orchards increase until expansion rates become low and lead to emission decreases. Furthermore, the yearly CO_2 emissions of grasslands and forests overall decrease.

Land use change partially contributes to the reduction of soil CO_2 emissions from secondary forests by 70.3% 2003 compared to 1994. Emissions of primary forests are 15.5% lower as well. The decreasing CO_2 emissions of forests together are much higher than the increasing CO_2 emissions from rubber, maize and paddy rice together. This can explain the yearly decrease of the entire watershed's CO_2 emissions throughout the entire simulation period.

Carbon Balance

The carbon balances per ha for the entire simulation period, in descending order, are less negative for rubber at LME, followed by rubber at HE, maize, orchards/tea, paddy rice, primary forests, grasslands, and secondary forests. Furthermore, they only present a few positive balances that can be observed in the case of rubber at LME from 1996 until 2001, as well as rubber at HE between 1997 and 2000 and in 2002. This may be mainly attributed to their strongly increasing biomasses and the simultaneously low fruit yields until 2000. The beginning of latex tapping at LME, i.e. an increase in exported carbon, leads to a more negative carbon balance for rubber at LME that reaches a balance similar to that of maize, orchards/tea and paddy rice. The carbon balance per ha of rubber at LME becomes the most negative one overall from 2002 onwards. This is due to the high latex exports in 2002 and 2003, which are overestimations of the LUCIA model.

Forests and grasslands have the most negative carbon balances per ha. This may be due to their constant biomasses, decreasing total soil carbon contents, the higher yields of forests compared to all other land uses, and the higher yields of grasslands compared to the remaining land uses (except for orchards/tea). Maize, orchards/tea and paddy rice have similar carbon balances that at the same time are less negative than those of forests and grasslands. Maize has the highest total soil carbon content with the lowest total soil carbon reduction rate, which can explain its less negative balance. Paddy rice has a somewhat more negative balance than maize, which may be attributed to paddy rice residues burning after harvest, its lower total soil carbon and it having the second lowest total soil carbon decrease. Orchards/tea has a similar biomass and yield than grasslands, but a 19.43 Mg C per ha lower total soil carbon decrease over the simulation, which explains its less negative balances. The least negative carbon balances in the watershed correspond to rubber at LME and HE. This may be because they have the watershed's strongest increasing biomass, the lowest yields until the beginning of tapping, and an at least 11.86 Mg C per ha lower total soil carbon decrease compared to forests, and only 7.27 Mg C per ha higher compared to maize. Moreover, less than 9 year old rubber plantations at LME are the most attractive carbon stocks in the watershed. Up to 11 year old rubber plantations at HE are the second most attractive carbon stocks in the study area.

The carbon balances per ha of all land uses become overall less negative as 2003 is approached. This can be attributed to the combination of several factors, which comprise the constant biomasses of all land uses – except for rubber that increases – throughout the simulation period, and the yields that start to overall decrease around 1996 onwards. Total soil carbon decreases throughout the simulation period, and is therefore the only factor that contributes to a more negative carbon balance. However, the rate of soil carbon decomposition decreases with time so that the overall carbon balance becomes less negative.

The carbon balance by land use area for every year and for the entire simulation period is negative for all land uses. Unlike on a hectare basis, rubber does not show a positive balance in any year. This is possibly due to the different ages of the rubber plantations that lead to overall lower rubber biomasses and/or to higher latex exports, thereby not allowing positive balances. Additionally, the less negative balances per ha at the end of the simulation period lead to less negative land use area balances as they approach 2003. Furthermore, the watershed's yearly carbon balance is negative over the simulation period, but also becomes less negative as 2003 approaches. This can be due to the less negative balances of all land use areas as the end simulation period comes near, and due to the reduction of secondary forests that have the watershed's most negative carbon balances per ha and the highest yields among the perennials until rubber plantations begin to be tapped and start having the most negative carbon balances per ha and some of the highest yields.

Model

The simulated biomasses per ha correspond to experimental estimates for Xishuangbanna and alternative locations used for calibrating the LUCIA model for this study (Chapter Five). They are somewhat higher than experimental estimates and differ by 5.82% for primary forests, 4.07% for secondary forests, 8.53% for grasslands, 0.35% for orchards/tea, and 2.96% for maize. Simulated paddy rice was 73.01% higher, which may be attributed to that the model’s planting density input option for annual crops does not react towards changes, thereby not allowing adjusting paddy rice biomass in that way. The LUCIA model’s annual crops module may need to be improved in this regard. Furthermore, simulated rubber biomass accumulation begins in year 3 after planting, when in reality it begins in year 1. It also experiences a somewhat strong biomass increase as it grows. However, when adding simulated and estimated rubber biomasses independently at one point for every year, the added biomasses are not significantly different ($p < 0.05$). As this study focuses on biomass carbon sequestration over the entire simulation period, the simulated rubber biomasses are suitable.

Simulated latex exports at LME reach 0.98 Mg C per ha in 2001. They correspond to the 0.95 Mg C per ha latex yields for 14 year old rubber plantations at ME in Xishuangbanna reported by Jia (2006). However, latex exports for 2002 and 2003 are overestimations of the LUCIA model, and surpass published estimates by up to 145.1% (Jia, 2006). They occur because the model changes the user-defined tapping frequency (every other day) to every day, every other day, and every three days. Thereby tapping days increase from about 100 (resulting from user-defined settings) to 165 days (resulting from the model’s incorrect reads). The LUCIA model’s rubber module needs to be improved so that tapping occurs at the user-defined frequency, which will lead to appropriate yearly latex exports.

Furthermore, the simulated biomass of the entire watershed is lower than the estimated one. This is possibly attributed to that the LUCIA model restricts biomass growth on the maps' pixels that present biomass growth restricting factors, such as high soil erosion and soil loss, among others. Therefore, simulated as well as estimated results are presented in this thesis. However, some model outputs could only be obtained on a hectare scale and not for the entire area, the carbon balance calculations were carried out solely with estimated results, so as to use homogeneous data.

Moreover, it was expected that the notably higher soil erosion per ha on rubber, maize and paddy rice plantations would have a more pronounced effect on topsoil carbon reduction, despite the higher litter inputs to paddy rice and maize. Additionally, it was not expected that litter would have such high influence on topsoil carbon compared to erosion, as in some cases maize topsoil depth decreases from around 15.0 to 5.5 cm during the simulation. The higher and more constant topsoil carbon contents of maize and paddy rice were expected, as they have high litter inputs due to cutting of the whole plant at harvest. The strong decrease of topsoil carbon of primary and secondary forests was unexpected, as the denser forest vegetation was expected to lead to higher litter inputs.

The yearly litter of Xishuangbanna's forests ranges from 0.89 to 4.21 Mg C per ha (Jia, 2006 and Ren et al., 1999). Although a forest litter input of 1.0 Mg C per ha was entered to the LUCIA model (Appendix B: Litter Initialization), it only added 0.15 Mg C per ha litter over the whole simulation. The same was observed for rubber plantations that have a litterfall of 0.75 to 3.78 Mg C per ha, and the model only allowed an input of 0.02 Mg C per ha throughout the simulation period. The LUCIA model's litter input module is differently parameterized for annual than for perennial crops, which can explain the lower litter inputs of perennials. It needs to be improved so that the litter input of perennials is higher than is actually predicted by LUCIA, and leads to a litter accumulation that is higher than carbon exports, and could thereby increase total soil carbon and consequently also lead to less negative carbon balances.

Furthermore, it is suggested to revise if there is a realistic relationship between soil erosion and topsoil carbon content.

The soil CO_2 emissions per ha of rubber were expected to be higher or at least closer to those of orchards/tea, due to their similar total soil carbon content and manure input. Furthermore, the simulated average daily CO_2 emissions are 0.034 Mg C per ha for primary forests and 0.033 Mg C per ha for secondary forests, 0.011 Mg C per ha for rubber at LME, and 0.009 Mg C per ha for rubber at HE. Experimental measurements in Xishuangbanna show that average daily CO_2 emissions only reach 0.017 Mg C per ha for primary forests, and 0.009 Mg C per ha for secondary forests. Rubber plantations have CO_2 emissions of 0.008 Mg C per ha (Werner et al., 2006), which are similar to the simulated ones. The simulated rubber is young, which may mean that actual CO_2 emissions are possibly being overestimated, as can be observed for forests. Therefore, it is recommended that the model's CO_2 emissions production module is adjusted so as to fit observed values. The model's overestimation of CO_2 emissions from forests affects the final carbon balance. It was not expected that the carbon balances per ha of all agricultural land uses would be the least negative ones. It was expected that forests and grasslands have close to neutral balances and not the most negative ones with between -7.93 and -16.94 Mg C per ha. Tropical rainforests in Xishuangbanna are carbon sinks that can store around 1.68 Mg C per ha per year (Zhang et al., 2010).

Overall, especially rubber at LE and ME can support the increase of carbon sequestration in the region compared to all other land uses, including mature secondary forests, but not primary forests. Nevertheless, suggesting whether promoting the replacement of secondary forests and of other land uses with rubber plantations is an appropriate approach to increase carbon sequestration or not, is not easy. Such replacement is likely to increase carbon sequestration and bring along attractive economic returns in terms of latex production, as well as possibly some type of financial benefit for mitigating carbon emissions. Furthermore, the increase of biomass carbon sequestration in rubber plantations can support the Chinese Government's goal to reduce carbon emissions from agricultural sources. Beyond these benefits, rubber plantations may to some extent also cause the reduction of biological diversity and of some ecosystem services, which may result in important negative socio-economic and environmental effects. As an example, farmers and scientists have already reported that the high water uptake of rubber plantations in Xishuangbanna, compared to other crops, is leading to the reduction of water resources (Tan et al., 2011), which is a vital resource for humans, agriculture, and to maintain a more stable climate, among others.

Moreover, conditions for the further expansion of rubber in the area in the coming years can be expected to remain favourable regarding the overall tendency of world natural rubber prices to increase, the availability of suitable land for rubber cultivation, the Chinese Government’s policies to promote rubber cultivation, and the continuous development of rubber clones that are more resistant to drought, frost, wind, and diseases. Additionally, these favourable conditions may even improve further by the option of using rubber plantations as carbon storages as a means to achieve China’s carbon emission reduction goals. Consequently, it can be expected that rubber will continue to expand, and thereby follow the trend of mainly replacing the NRWNNR’s forests.

Xishuangbanna’s current and expected future situation regarding the expansion of rubber plantations calls for the consideration of measures that aim at avoiding and decreasing negative environmental and socio-economic effects in the area. Therefore, it is important to carefully consider the extent to which rubber plantations are environmentally and socio-economically suitable as a measure for improving the area’s carbon balance, as well as for increasing rural income. Furthermore, it is likely that without sufficient policy changes to promote a more controlled rubber expansion in the area, rubber will possibly keep replacing vegetation types with a higher biological diversity, like primary and secondary forests, as well as less resource-intensive crops. Therefore, it is suggested that policies aiming at increasing carbon sequestration, at rapidly increasing rural income or reducing national dependency on imports based on the rapid expansion of a single crop, like rubber, should not be viewed as single issues. In order to be sustainable in the long-term, such policies need to consider other relevant effects, especially those that could have important negative effects on the regions' environmental, socio-economic and political stability.