CHAPTER 4

RESULTS

4.1 Biomass and Carbon Sequestration of Selected Land Uses in the Naban River Watershed National Nature Reserve

Since the 1970s, the NRWNNR is subject to the increasing expansion of rubber at elevations below 1000 m (Fox et al., 2009 and Fox et al., 2011, p. 12-13). Along with recent developments of high yielding frost-resistant rubber clones (Lu et al., 2010, p. 5) comes the threat of deforestation at even higher elevations. This poses a threat not only to the already affected tropical seasonal and montane rainforests, but also to subtropical evergreen broadleaf forests at above 1000 m. In order to estimate to which extent land use change alters the carbon sequestration potential, CO_2 emissions and carbon balance in the NRWNNR over time, it is necessary to estimate the carbon sequestration potential of its different land uses.

Therefore, the first part of this chapter refers to carbon storage in biomass (i.e. aboveground and belowground biomass) of rubber plantations at different locations, namely western Ghana, Mato Grosso (Brazil), Hainan Island (China), Xishuangbanna, and the NRWNNR. The second part of this chapter presents the carbon sequestration in biomass of other large land uses in the NRWNNR, i.e. plantations of paddy rice and maize, orchards/tea, grasslands; and primary and secondary tropical seasonal rainforests, montane rainforests, and subtropical evergreen broadleaf forests.

There are several different approaches in the derivation of allometric equations to estimate plant biomass. An allometric equation gives an estimation of plant biomass based on one or more tree measurements, such as diameter at breast height and tree height (UNFCCC/CDM Executive Board, 2011, p. 1). A study by Fang et al. (1998) shows that the use of three different methods (i.e. biomass to volume relationship, average biomass density, and average biomass to stem volume ratio) for the estimation of forest biomass in China had a discrepancy of 80% between the highest and lowest estimates (Fang et al., 1998, p. 1084–1091). Therefore, even though a lot of information may be available about specific vegetation types or crops, its accurate conversion into biomass estimates is still a big limitation in ecosystem carbon studies (Li et al., 2008, p. 22).

4.1.1 Rubber

Using the studies of Jia (2006) and Song and Zhang (2010) as a reference for the consideration of different elevation ranges in Xishuangbanna, this study differentiates among low elevations (hereafter LE) at 530 to 650 m, medium elevations (hereafter ME) at 680 to 800 m, and high elevations (hereafter HE) at 870 to 1050 m. In order to estimate rubber biomass, allometric relationships are considered, as well the elevation gradient, which is an important determinant for climate variation – especially temperature – that significantly influences rubber tree biomass development.

4.1.1.1 Western Ghana and Mato Grosso

The assessed rubber plantations in western Ghana (WG) and Mato Grosso (MG), Brazil have a tree density of 476 to 550 trees per ha. In WG the elevation is about 133 m and the soil pH is 4.6. The rainfall is between 1200 and 1800 mm per year and the relative air humidity reaches 95 to 100%. The annual mean temperature is 24 to 27° C, while lowest and highest temperatures reach 15 and 40° C. The elevation in MG is 500 m and the soil pH is 5. It rains 1500 to 2000 mm per year and the relative air humidity is 76%. The annual mean temperature is 24° C, while the lowest and highest temperatures are 1 and 40° C (Wauters et al., 2008, p. 2347-2349).

The biomass and carbon sequestration was studied in 2 to 14 year old plantations in WG, and in 3 and 14 to 24 year old plantations in MG. DBH is calculated at a height of 1.7 m[13], and the calculated conversion factor of biomass into carbon is 48.70%. The biomass of a 14 year old rubber plantation in WG is 156.76

[13] This is mentioned, as the DBH is usually measured at a height of 1.3 m from the ground.

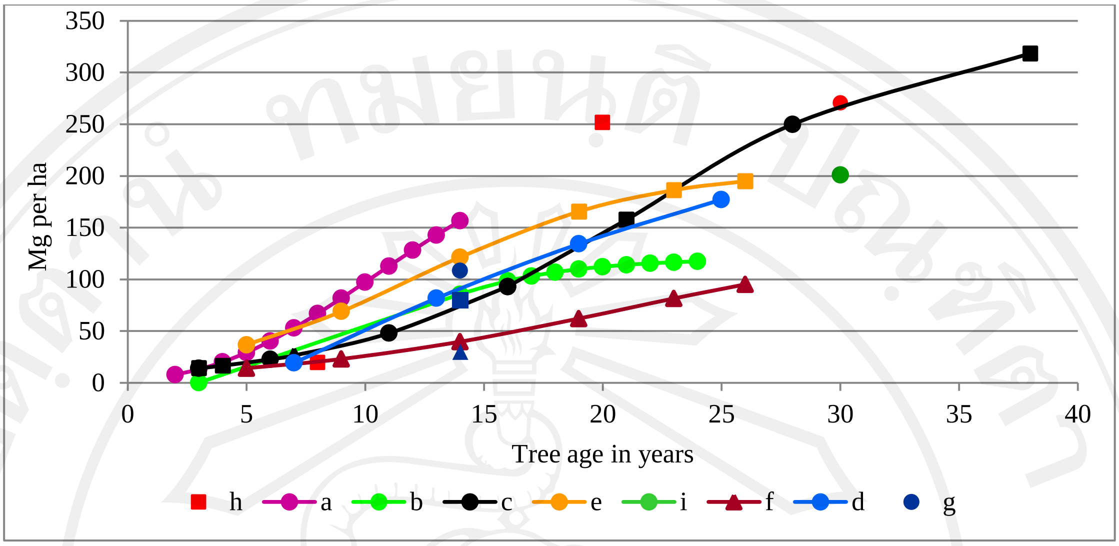
Mg per ha, i.e. 76.34 Mg C per ha, while in MG it is 85.66 Mg per ha, i.e. 41.72 Mg C per ha (Figure 11). The average annual carbon sequestration rate is 3.89 Mg C per ha in WG, and 2.50 Mg C per ha in MG. The difference in carbon sequestration is attributed to the different tree height (e.g., 19 to 24 m in WG and 10 m in MG at 14 years) and girth at both sites. The average biomass distribution in WG corresponds to 88.4% in aboveground biomass and 11.6% in belowground biomass, while in MG it is 81.5% and 18.5%, respectively (Wauters et al., 2008).

4.1.1.2 Xishuangbanna

Yang et al. (2005) estimated rubber biomass in Xishuangbanna using Brown's and Tang's allometric equations; however, biomass data calculated using Tang's equation are omitted here, as they seem to be an overestimation when compared to all other authors' data. The studied rubber plantations have a tree density of 450 trees per ha. The elevations are between 550 and 895 m, and the slopes are between 5° and 20°. The biomass and carbon sequestration were assessed for trees of 3, 4, 6, 7, 11, 16, 21, 28 and 38 years. The conversion factor of biomass into carbon is 50.0%[14]. The biomass of the plantations is of 3.10 up to 326.50 Mg per ha, i.e. 1.55 to 163.25 Mg C per ha (Figure 21). The mean annual carbon sequestration rate is 2.35 Mg C per ha (Yang et al., 2005, p. 298-300).

Tang et al. (2009) calculated the biomass of rubber trees with ages of 7, 13, 19, 25 and 47 years. The elevations are between 565 and 640 m, and the slopes are 2.5° to 32.5°. The estimated biomass is of 23.98 to 250.21 Mg per ha, i.e. 11.99 and 125.11 Mg C per ha (Figure 21). Furthermore, the share of aboveground and belowground biomass in Xishuangbanna is different across different ages (Table 5). The average biomass share is 81.4% in aboveground and 18.6% in belowground biomass (Tang et al., 2009, p. 1942, 1944-1945).

[14] The standard conversion factor to compute carbon content from biomass is 0.5 kg C per kg of biomass.



● stands for LE, ■ for ME, and ▲ for HE
a: western Ghana (Wauters et al., 2008)
b: Mato Grosso (Wauters et al., 2008)
c: LE, ME Xishuangbanna (Yang et al., 2005)
d: LE Xishuangbanna (Tang et al., 2009)
e: LE, ME Xishuangbanna (Song and Zhang, 2010)
f: HE Xishuangbanna (Song and Zhang, 2010)
g: LE, ME, HE Xishuangbanna (Jia, 2006)
h: LE, ME Xishuangbanna (Bao et al., 2008)
i: Hainan (Cheng et al., 2007)

Figure 21 Biomass in Mg per ha of rubber plantations in western Ghana, Mato Grosso, Xishuangbanna, the NRWNNR, and Hainan Island

Song and Zhang's (2010) study separated RRIM600 rubber plantations into two elevations, a LE+ME, and a HE. The plantations' ages are 5, 9, 14, 19, 23 and 26 years. The lowest and highest amounts of aboveground biomass are 16.47 and 192.92 Mg per ha at LE+ME, and 9.40 and 91.22 Mg per ha at HE, i.e. that carbon sequestration is 8.24 to 94.46 Mg C per ha at LE+ME, and 4.70 and 45.61 Mg C per ha at HE (Figure 21). The average rate of annual carbon sequestration is 3.36 Mg C per ha at the LE+ME, and 1.42 Mg C per ha at the HE (Song and Zhang, 2010, p. 1887-1889).

Table 5 Share of aboveground and belowground biomass in % of rubber trees of ages 7, 13, 19, 25 and 47 years at low elevations in Xishuangbanna

Age in years	Aboveground biomass in %	Belowground biomass in %
7	73.80	26.20
13	79.12	20.88
19	82.66	17.34
25	83.58	16.42
47	87.62	12.38

(Tang et al., 2009, p. 1945)

Jia (2006) estimated the aboveground biomass of 14 year old RRIM600 rubber plantations at LE, ME and HE. The slopes are 15° to 20°. The aboveground biomass is 108.35±11.48 Mg per ha at LE, 79.71±14.48 Mg per ha at ME, and 29.93±4.12 Mg per ha at HE, i.e. 54.18±5.74, 39.86±7.24 and 14.97±2.06 Mg C per ha, respectively. The average annual aboveground carbon accumulation at LE, ME and HE is 3.05, 3.41 and 1.85 Mg C per ha, correspondingly (Jia, 2006, p. 3-4, 21), which is confirmed by Song and Zhang's (2010, p. 1889) results. This shows the strong influence that different elevations have on biomass development (Figure 21). Furthermore, the aboveground biomass allocation in stems, branches and leaves is different at different elevation ranges (Table 6; Jia, 2006, p. 3).

Table 6 Aboveground biomass allocation of 14 year old rubber trees at low, medium and high elevations in Xishuangbanna

Elevation	Stem in %	Branches in %	Leaves in %
Low	83.93	12.67	3.40
Medium	72.88	21.89	5.23
High	71.58	23.19	5.23

(Jia, 2006, p. 3)

Bao et al. (2008) estimated the aboveground biomass of 8 to 9, 20, and 30 to 33 year old rubber plantations at elevations of 730 m, 703 m, and 595 m, respectively. Their tree densities are 716, 320 and 386 per ha, and their tree heights range from 7 to 9 m, 24 to 30 m, and 25 m, respectively. The biomass is 19.69 to 270.79 Mg per ha, i.e. 9.85 and 135.40 Mg C per ha (Figure 21). The average annual carbon sequestration rate is of 4.01 Mg C per ha (Bao et al., 2008, p. 736-737).

4.1.1.3 Hainan Island

The mean annual rainfall in Hainan Island, China lies between 1600 and 2500 mm, and the mean yearly temperature ranges between 23 and 25° C. Trees with an average DBH of 20 cm and an age of 30 years were used to calculate the carbon sequestration of rubber plantations in the area. The planting density is usually about 375 trees per ha. Furthermore, the studied plantations tend to have a yearly nitrogen, potassium and magnesium deficit of 13.07, 23.41, and 4.07 kg per ha, correspondingly. Nevertheless, during a 30 years life span, rubber can build up a biomass of 201.02 Mg per ha, and thereby sequester 100.51 Mg C per ha. The mean carbon accumulation rate is of 3.35 Mg C per ha per year (Cheng et al., 2007, p. 349, 351).

4.1.2 Calculation of Rubber Tree Biomass in the Naban River Watershed National Nature Reserve

Since available data to estimate the biomass of rubber trees at LE and HE in the NRWNNR could not be assessed by the author, alternative information from a literature review (Yang et al., 2005; Song and Zhang, 2010; Tang et al., 2009; Bao et al., 2008 and Jia, 2006) concerning biomass data of rubber trees in Xishuangbanna in general is described here. The biomass at ME was estimated with data from 2009 and 2010 of 142 rubber trees from the NRWNNR from which girth at breast height, height, ages (9, 10, 11, 12, 15, 16, 21, 22, 23 and 24 years), elevations (680 to 700 m), and clone types (RRIM600 and GT1) were available (Golbon, 2012, personal communication). The biomass estimation at ME is further supported with data from literature (Yang et al., 2005; Song and Zhang, 2010; Bao et al., 2008 and Jia, 2006).

The biomass in kg per tree is computed using the allometric equation from Ketterings

$$B = aD^b, \qquad (2)$$

where B is biomass per tree in kg, a and b are parameters to be estimated, and D is the DBH of each tree in cm. Ketterings' equation is suitable, as its parameters a and b can be set for each location specifically, and it includes the average wood density (ρ) in g per cm^3 of the site as

$$a = r\rho, \qquad (3)$$

where r is the specific site index. Furthermore, this equation can be applied with or without having data about the tree height (H) in m. However, this equation cannot be used until a tree age of about 4 years, as it is only valid for diameters from 10 to 38 cm (Ketterings et al., 2001, p. 199 and Janssens et al., 2003, p. 98). For LE and HE, b is estimated from the site specific relationship (x-y scatter relationship plot) between ln(D) and ln(B). For ME, b can be taken as

$$b = 2+c, \tag{4}$$

where c is estimated from the site specific relationship (x-y linear relationship plot) between D in cm and H in m. Parameter a is estimated from

$$a = \mu_i/D_i^b, \tag{5}$$

where μ_i is the mean biomass of all trees with diameters D_i, and D_i is their DBH (Ketterings et al., 2001, p. 202-203, 206-207). As there is a large difference in biomass accumulation at different elevations (Jia, 2006, p. 3 and Song and Zhang, 2010, p. 1889), regression models were developed for the three different elevation ranges, LE, ME, and HE (Table 7).

Table 7 Tree biomass regression models for rubber plantations at low, medium and high elevations in the NRWNNR

Organ	Elevation	Regression models	Correlation coefficient	SE of a
Aboveground	Low	$0.1042{*}D^{2.4750}$	0.9850	0.00220
	Medium	$0.4528{*}D^{2.0479}$	1.0000	7.98E-17
	High	$0.1089{*}D^{2.5040}$	0.9820	0.00498
Stem	Low	$0.0874{*}D^{2.4750}$	0.9850	0.00185
	Medium	$0.3300{*}D^{2.0479}$	1.0000	7.94E-17
	High	$0.0780{*}D^{2.5040}$	0.9820	0.00356
Branch	Low	$0.0132{*}D^{2.4750}$	0.9850	0.00028
	Medium	$0.0991{*}D^{2.0479}$	1.0000	2.66E-17
	High	$0.0253{*}D^{2.5040}$	0.9820	0.00115
Leaf	Low	$0.0035{*}D^{2.4750}$	0.9850	7.48E-05
	Medium	$0.0237{*}D^{2.0479}$	1.0000	3.27E-18
	High	$0.0057{*}D^{2.5040}$	0.9820	0.00026
Belowground	Low	$0.0239{*}D^{2.4750}$	0.9850	0.00050
	Medium	$0.1038{*}D^{2.0479}$	1.0000	1.07E-17
	High	$0.0250{*}D^{2.5040}$	0.9820	0.00114
Total	Low	$0.1281{*}D^{2.4750}$	0.9850	0.00270
	Medium	$0.5566{*}D^{2.0479}$	1.0000	0.03895
	High	$0.1339{*}D^{2.5040}$	0.9820	0.00611

Other common equations, like the ones from Brown, $B = 42.69–12.8D+1.242D^2$ and $B = e^{(-2.134+2.53\ln(D))}$ have already set parameters, so they may not be site specific. Furthermore, they are too general to estimate rubber biomass, since they have been developed with data from many different tree species (Janssens et al., 2003, p. 97). Additionally, Brown's equation can lead to an overestimation factor of up to 2 in secondary forests and fast growing trees (Hairiah et al., 2001, p. 9). As this study requires the use of literature data to develop allometric equations, Tang's equation, $B = a(D^2H)^b$ (Tang et al., 2009, p. 1944) cannot be applied easily, as H is often omitted in literature, and usually only D can be derived from rubber biomass data found in literature.

Rubber plantations in Xishuangbanna have a tree density of about 450 trees per ha (Yang et al., 2005, p. 298 and Jia, 2006, p. 10). This tree density is used throughout this thesis to support the biomass estimation of rubber plantations in the NRWNNR. As an example, the total biomass per ha (450 trees per ha) of 14 year old rubber plantations with DBHs of 21.69 cm at LE, 17.43 cm at ME and 10.26 cm at HE (Song and Zhang, 2010 and Jia, 2006) in the NRWNNR is 116.95, 87.26 and 20.51 Mg per ha, respectively (calculated after Table 7). The aboveground and belowground biomasses correspond to 95.13 and 21.82 Mg per ha at LE, 70.99 and 16.27 Mg per ha at ME, and 16.68 and 3.83 Mg per ha at HE (Figure 22), which is confirmed by the results of Jia (2006, p. 3). Therefore, at 14 years a rubber plantation can store 58.48, 43.63 and 10.26 Mg C per ha, respectively. Furthermore, the biomass accumulation is significantly different ($p < 0.05$) at the three elevation ranges.

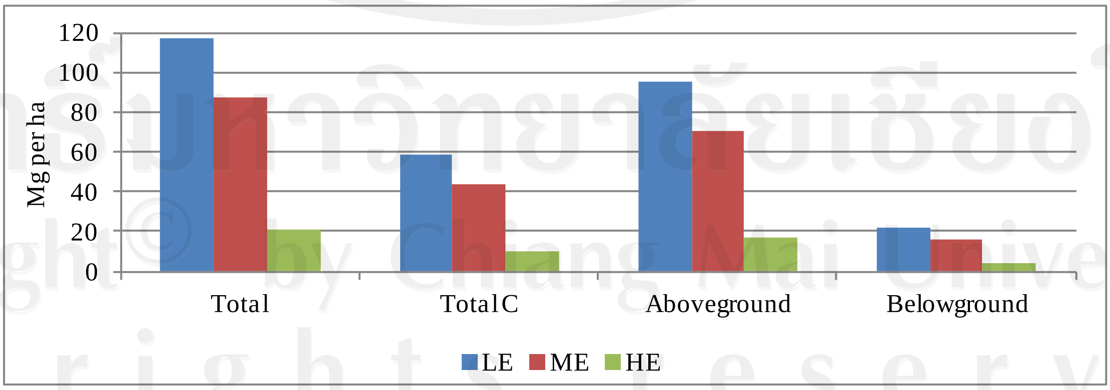


Figure 22 Total, total C, aboveground and belowground biomass in Mg per ha (450 trees per ha) of a 14 year old rubber plantation at low, medium and high elevations in the NRWNNR

A suitable sigmoid growth function to express rubber growth in dependence of time is the beta growth function

$$w = c_m t \left(\frac{2t_e - t_m - t}{2t_e - t_m}\right)\left(\frac{t}{t_m}\right)^{\frac{t_m}{t_e - t_m}}, \quad (5)$$

where w is the biomass in Mg per ha, c_m is the maximum growth rate in Mg per ha that is reached at time t_m, t_m is the plant's age at its maximum growth rate, t is the plant's age, and t_e is the time at the end of the growth period (Yin et al., 2003, p. 363, 371). In the case of rubber $t_e = 38$ is suitable, as its economic life is around 30 years and it needs about 8 years to reach a tappable girth. Table 8 presents the respective time-dependent functions to compute aboveground, stem, branch, leaf, belowground and total biomass of rubber plantations in Mg per ha for a tree density of 450 trees per ha at LE, ME and HE in the NRWNNR.

Table 8 Biomass regression models for rubber plantations (450 trees per ha) at low, medium and high elevations in the NRWNNR

Organ	Elevation	Regression model	SE
Aboveground	Low	$(7.2214t-0.1165t^2)(t/14)^{0.5833}$	10.28
	Medium	$(6.1059t-0.0911t^2)(t/9)^{0.3103}$	8.17
	High	$(3.0178t-0.0437t^2)(t/7)^{0.2258}$	3.87
Stem	Low	$(6.0609t-0.0978t^2)(t/14)^{0.5833}$	8.63
	Medium	$(4.4499t-0.0664t^2)(t/9)^{0.3103}$	5.96
	High	$(2.1601t-0.0313t^2)(t/7)^{0.2258}$	2.77
Branch	Low	$(0.9150t-0.0148t^2)(t/14)^{0.5833}$	1.30
	Medium	$(1.3366t-0.0199t^2)(t/9)^{0.3103}$	1.79
	High	$(0.6998t-0.0101t^2)(t/7)^{0.2258}$	0.90
Leaf	Low	$(0.2455t-0.0040t^2)(t/14)^{0.5833}$	0.35
	Medium	$(0.3193t-0.0048t^2)(t/9)^{0.3103}$	0.43
	High	$(0.1578t-0.0023t^2)(t/7)^{0.2258}$	0.20
Belowground	Low	$(1.6549t-0.0267t^2)(t/14)^{0.5833}$	2.36
	Medium	$(1.3993t-0.0209t^2)(t/9)^{0.3103}$	1.87
	High	$(0.6916t-0.0100t^2)(t/7)^{0.2258}$	0.89
Total	Low	$(8.8763t-0.1432t^2)(t/14)^{0.5833}$	12.64
	Medium	$(7.5052t-0.1120t^2)(t/9)^{0.3103}$	10.05
	High	$(3.7093t-0.0538t^2)(t/7)^{0.2258}$	4.75

During a life span of 38 years, rubber plantations in the NRWNNR can build up a biomass of 233.68±12.64, 193.05±10.05, and 92.70±4.75 Mg per ha at LE, ME, and HE (Figure 23), i.e. 116.84±6.32, 96.53±5.03, and 46.35±2.38 Mg C per ha, respectively (calculated after Table 8). The average annual biomass accumulation at LE, ME and HE corresponds to 6.15±0.33, 5.08±0.26, and 2.44±0.13 Mg per ha. If the biomass of rubber plantations per ha at LE, ME and HE in the NRWNNR is averaged, than, their average biomass is of 173.14 Mg per ha, i.e. 86.57 Mg C per ha, which represents a yearly biomass increment of 4.56 Mg per ha.

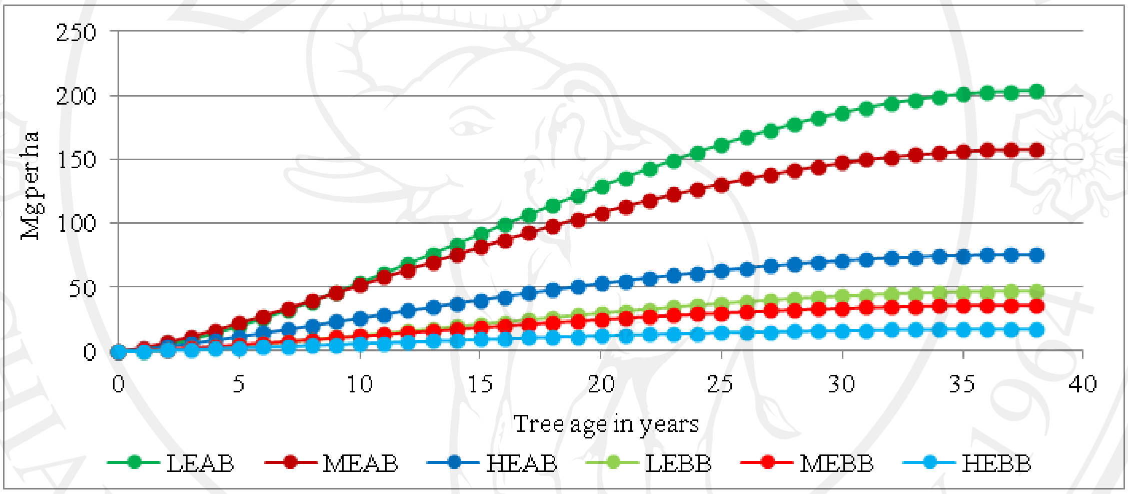


Figure 23 Aboveground (AB) and belowground (BB) biomass in Mg per ha of 0 to 38 year old rubber plantations at low, medium and high elevations in the NRWNNR

In more suitable cultivation areas like western Ghana, carbon sequestration in 30 year old plantations can be from 20.14 up to 83.64 Mg C per ha higher than at LE and HE in the NRWNNR, in Hainan Island 6.68 less up to 56.82 Mg C per ha more, and in Mato Grosso 48.87 less up to 14.63 Mg C per ha more.

The biomass accumulation of rubber plantations in the NRWNNR is significantly affected by the different elevations ranges. It shows a negative correlation as elevation increases, which is confirmed by the results for Xishuangbanna of Jia (2006, p. 3) and Song and Zhang (2010, p. 1889). Several studies show that usually lower elevations have a larger biomass increase than higher elevations, as the temperature tends to be higher, which increases the growing season. A longer growing season contributes to improve the metabolic activity of a plant, such that photosynthesis rate and cell growth can further increase. The temperature is usually lower at higher elevations, whereby biomass development may be restricted (Song and Zhang, 2010, p. 1890).

When stem, branch, and leaf biomass are taken into account separately, they show to be significantly different (< 0.05) at the different elevations ranges. The biomasses of 14 year old trees at LE, ME and HE correspond to 79.79, 51.73 and 11.95 Mg per ha in the stem, 12.05, 15.54 and 3.87 Mg per ha in the branches, and 3.20, 3.72 and 0.87 Mg per ha in the leaves (calculated after Table 7). The difference between stem biomasses can be partially attributed to the different average heights of 14 year old trees, which are 16.27±0.54 m at LE, 15.08±1.06 m at ME, and 9.75±0.35 m at HE (Jia, 2006, p. 10). Nevertheless, branch and leaf biomass do not follow the pattern of aboveground and belowground biomass partitioning of Figure 23, where biomass at LE > biomass at ME, and > biomass at HE.

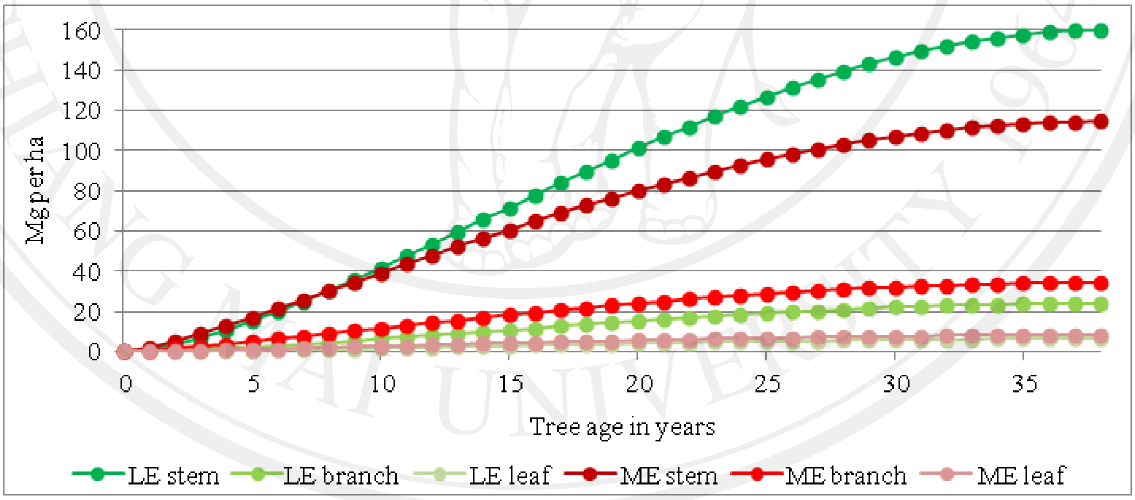


Figure 24 Stem, branch and leaf biomass in Mg per ha of 0 to 38 year old rubber plantations at low and medium elevations in the NRWNNR

This exception shows that branch and leaf biomass at ME is significantly higher (< 0.05) than at LE (Figure 24). This may occur due to the temperature inversion that happens during most part of the winter in the study area, and possibly faster developing plant organs benefit from such conditions. The temperature is overall higher at LE during most part of the year (Jiang, 1981, p. 276-278), which in turn can partly explain the larger stem biomass at LE. Stems develop more slowly, and at ME they may not benefit from the temporary temperature inversion for sufficient time to surpass stem biomass at LE.

Regression models were developed for estimating rubber tree biomass at LE, ME and HE. Further improvement can be achieved by considering the evaluation and inclusion of a fourth elevation range (ca. 780 to 870 m) to increase the accuracy of biomass estimation. However, the author could not access enough data to confirm this nor develop a regression model. Furthermore, the difference in rubber biomass estimations (Figure 21) can probably partly be explained by the use of different allometric equations that can lead to high discrepancies (Li et al., 2008, p. 22). In order to increase the accuracy of biomass estimations for Xishuangbanna, the author suggests carrying out two steps. The first one is to estimate rubber tree biomass with destructive methods using a representative sample at least at LE, ME and HE and for sufficient different tree ages. The data are then kept in an accessible database that enables more reliable biomass estimations in the future without requiring further destructive methods. The second step is the introduction of a voluntary standardized way of publishing the results of rubber biomass estimations (e.g. including tree heights and diameters in an annex).

4.1.3 Paddy Rice, Maize, Orchards/tea, Grasslands and Forests

This part of the chapter presents the amount of carbon that can be stored in the biomass of paddy rice and maize plantations, orchards/tea, grasslands, and of primary and secondary tropical seasonal rainforests, tropical montane rainforests, and subtropical evergreen broadleaf forests in the NRWNNR.

4.1.3.1 Paddy Rice, Maize, Orchards/tea and Grasslands

Paddy rice in Xishuangbanna has a biomass of above 12.02 Mg per ha, i.e. that with a conversion factor from biomass to carbon of 45%, it can store 5.41 Mg C per ha (Li et al. 2008, p. 18, Wehner, 2007, p. 15 and Devêvre and Horwáth, 2000). Accurate information regarding the carbon sequestration of the NRWNNR or Xishuangbanna's grasslands, orchards/tea and maize could not be accessed by the author. Alternatively, the following average biomasses were used: 25.00 Mg per ha for maize, 30.00 Mg per ha for woody grassland (Marohn, 2012, personal communication), and 28.52 Mg per ha for orchards/tea (Li et al. 2008, p. 19).

4.1.3.2 Primary Tropical Seasonal Rainforests

Forest biomass estimations by all authors include trees, shrubs, woody lianas, and herbs, unless stated otherwise. Li et al. (2008) estimated that the biomass (DBH ≥ 5 cm) of primary mature tropical seasonal rainforests is 243.48±13.98 Mg per ha, i.e. 121.74±6.99 Mg C per ha (Li et al., 2008, p. 18; Table 9). Lu et al. (2006) calculated the biomass (DBH ≥ 2 cm) to be 256.00 Mg per ha, i.e. 128.00 Mg C per ha (Lu et al., 2006, p. 277), which confirms Li et al.'s (2008) results. Zheng et al. (2006) assessed the biomass of mature forests (DBH ≥ 5 cm; tree height > 30 m) at elevations of 730, 740, and 1130 m. The tree densities per ha are 793, 730, and 489, respectively. The total biomass ranges from 362.09 to 497.13 Mg per ha, having an average of 420.18 Mg per ha, i.e. 210.09 Mg C per ha (Zheng et al., 2006, p. 318-319, 321). Data of two sampling plots are omitted as biomass is an overestimation when compared to all other authors' studies.

Lü et al. (2009) studied mature forests (DBH ≥ 2 cm; tree height > 40 m). The mean biomass is 403.66 (332.00 to 523.00) Mg per ha, i.e. 201.83 (166.00 to 261.50) Mg C per ha (Lü et al., 2009, p. 212), which confirms the results of Zheng et al. (2006, p. 321). The tree layer alone stores an average of 198.33 (162.60 to 258.30) Mg C per ha. The different amount in carbon storage is mostly explained by the different densities of big trees with a DBH above 70 cm (Lü et al., 2010, p. 1798, 1800). Feng et al. (1998) estimated that the forest biomass (DBH ≥ 5 cm) is 360.91 Mg per ha, i.e. 180.45 Mg C per ha (Feng et al., 1998, p. 481), which is close to the results of Lü et al. (2009) and Zheng et al. (2006). The average biomass of a primary tropical seasonal rainforest is 366.33 Mg per ha, i.e. 183.16 Mg C per ha.

In average, 97.95% of the biomass (DBH ≥ 5 cm for trees; DBH ≥ 2 cm for lianas) is in trees, 1.11% in shrubs, 0.83% in lianas, and 0.17% in herbs. The average biomass distribution in trees is 76.5 to 81.9% in aboveground biomass and 19.8 to

21.8% in belowground biomass (Zheng et al., 2006, p. 318; Lü et al., 2009, p. 212 and Feng et al., 1998, p. 481, 484). Furthermore, trees with a DBH of 70 cm and above make up 46±13% of the biomass (Lü et al., 2010, p. 1801), which shows that big trees are important for carbon storage in the NRWNNR's primary tropical seasonal rainforests.

Table 9 Biomass estimations of Xishuangbanna's primary tropical seasonal rainforests

Authors	DBH in cm	Tree height in m	Biomass in Mg/ha	C in Mg/ha
Li et al., 2008	≥ 5	-	243.48	121.74
Lu et al., 2006	≥ 2	-	256.00	128.00
Zheng et al., 2006	≥ 5	> 30	362.09 and 497.13	181.05 and 248.57
Lü et al., 2009	≥ 2	> 40	332.00, 356.00 and 523.00	166.00, 178.00 and 261.50
Feng et al., 1998	≥ 5	-	360.91	180.45
Average	-	-	366.33	183.16

(Li et al., 2008; Lu et al., 2006; Zheng et al., 2006; Lü et al., 2009 and Feng et al., 1998)

Zheng et al. (2006) and Bao et al. (2008) classified the forests in Table 10 as primary tropical seasonal rainforests. However, the elevations of 953 up to 1130 m at which they are located suggest that they may be primary tropical montane rainforests, which are normally located between 700 and 1500 m. Nevertheless, these forests show biomasses close to those of primary tropical seasonal rainforests (Table 9), which usually lie below 800 and 900 m.

Table 10 Biomass estimations of Xishuangbanna's primary tropical rainforests at high elevations

Authors	DBH in cm	Tree height in m	Biomass in Mg/ha	C in Mg/ha	Elevation in m
Bao et al., 2008	≥ 5	> 50	381.46	190.73	953
	≥ 5	> 40	317.01	158.51	979
	≥ 5	< 38	311.16	155.58	1070
Zheng et al., 2006	≥ 5	> 30	401.32	200.66	1130
Average	≥ 5	-	352.74	176.37	-

(Zheng et al., 2006 and Bao et al., 2008)

4.1.3.3 Primary Tropical Montane Rainforests and Secondary Tropical Seasonal and Montane Rainforests

The biomass (DBH ≥ 5 cm) of primary tropical montane rainforests reaches 232.48±7.66 Mg per ha, i.e. 116.24±3.83 Mg C per ha (Li et al., 2008, p. 19). Furthermore, Li et al. (2008) estimated the biomass of secondary seasonal and secondary montane rainforests like one forest type as they have similar biomasses. The forests have a biomass (DBH ≥ 5 cm) of 58.46±6.10 Mg per ha, i.e. 29.23±3.05 Mg C per ha when they are young (age less than 10 years), 112.12±7.50 Mg per ha, i.e. 56.06±3.75 Mg C per ha at an intermediate stage (11 to 20 years), and 150.34±8.36 Mg per ha, i.e. 75.17±4.18 Mg C per ha at maturity (over 21 years; Li et al., 2008, p. 19, 22).

Li et al.'s (2008) results are similar to Tang et al.'s (1998) biomass estimation of secondary tropical seasonal rainforests of ages 5, 10, 14 and 22 years, which have a mean tree height of 7.0, 8.3, 8.7 and 10.6 m, and lie at elevations between 585 and 620 m. The biomass is 41.94, 52.12, 88.28, and 113.74 Mg per ha, respectively, i.e. 20.97, 26.06, 44.14, and 56.87 Mg C per ha. This means that mature (over 21 years) secondary montane and seasonal tropical rainforests have an average biomass of 132.04 Mg per ha, i.e. 66.02 Mg C per ha. Furthermore, trees make up more than 80% of the forest biomass (Tang et al., 1998, p. 489-490), which is about 18% lower than in primary tropical seasonal rainforests. The average annual carbon accumulation rate of secondary tropical seasonal and montane forests in Xishuangbanna is around 3.07 Mg C per ha per year (Li et al., 2008, p. 19 and Tang et al., 1998, p. 490).

4.1.3.4 Primary and Secondary Subtropical Evergreen Broadleaf Forests

Li et al. (2008) estimated that the biomass (DBH ≥ 5 cm) of a primary subtropical evergreen broadleaf forest reaches 210.48±7.98 Mg per ha, i.e. 105.24±3.99 Mg C per ha (Li et al., 2008, p. 18). Li et al. (2006) came to the result that forest biomass ranges between 204.00 and 318.00 Mg per ha, i.e. 102.00 and 159.00 Mg C per ha (Li et al., 2006, p. 1), confirming Li et al.'s (2008, p. 18) results. This makes an average of 244.16 Mg per ha and 122.08 Mg C per ha.

Secondary subtropical evergreen broadleaf forests have a biomass of 64.30±5.28 Mg per ha and 32.15±2.64 Mg C per ha when they are young (below 20 years), 109.46±3.78 Mg per ha and 54.73±1.89 Mg C per ha at an intermediate stage (21 to 50 years), and 142.00±6.08 Mg per ha and 71.00±3.04 Mg C per ha at maturity (over 51 years). Their mean biomass is 106.44±4.26 Mg per ha and 53.22±2.13 Mg C per ha. The mean annual carbon accumulation rate of a secondary subtropical evergreen broadleaf forest is 0.80 (below 20 years), 1.10 (21 to 50 years), 1.39 (over 51 years), and 2.19 Mg C per ha (0 to over 51 years; Li et al., 2008, p. 18-19).

The yearly carbon accumulation rate in secondary vegetation is highest in rubber plantations at LE with 3.17±0.11 Mg C per ha, followed by secondary tropical seasonal and montane forests with 3.07 Mg C per ha (Li et al., 2008, p. 19 and Tang et al., 1998, p. 490) and rubber plantations at ME with 3.06±0.06 Mg C per ha. Then come secondary subtropical evergreen broadleaf forests with 2.19 Mg C per ha (Li et al., 2008, p. 19) and rubber plantations at HE with 1.55±0.03 Mg C per ha.

As a means of comparison with mature rubber (38 years old) that stores 86.57 Mg C per ha when averaging biomass carbon per ha of mature rubber at LE to HE, the average carbon sequestration of the different land uses in the NRWNNR, in ascending order, is 5.41 Mg C per ha in rice – 93.75% less than in rubber, 66.02 Mg C per ha in mature secondary seasonal tropical and montane rainforests – 23.76% less, 71.00 Mg C per ha in mature secondary subtropical evergreen broadleaf forests – 18.01% less, 116.24 Mg C per ha in primary tropical montane rainforests – 34.23% more, 122.08 Mg C per ha in primary subtropical evergreen broadleaf forests – 40.97% more, and 183.16 Mg C per ha in primary tropical seasonal rainforests – 111.50% more (Figure 25).

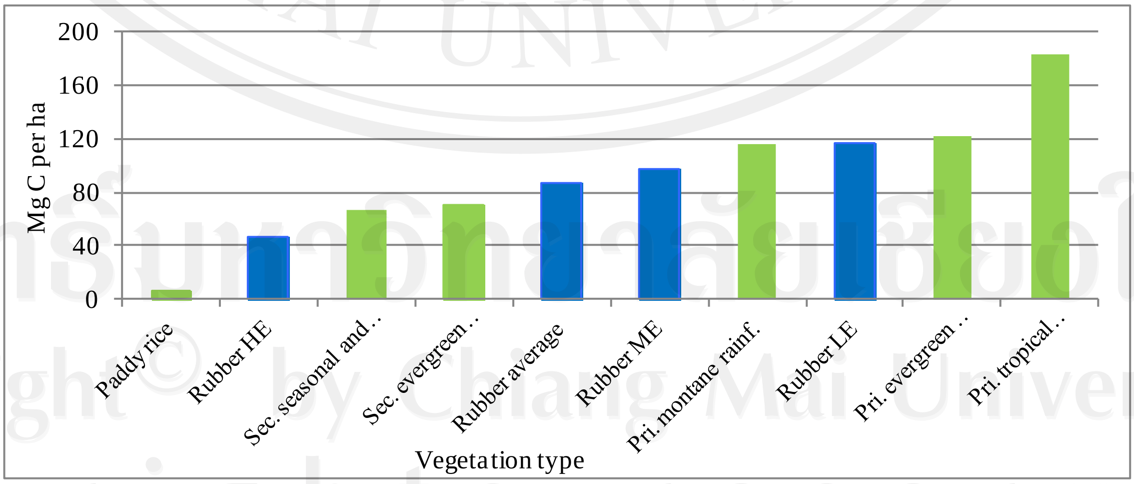


Figure 25 Biomass carbon estimations in Mg C per ha of mature rubber, paddy rice, and primary and secondary forests in Xishuangbanna

The higher biomass of primary tropical seasonal rainforests compared to rubber, and the higher rubber biomass at LE and ME compared to secondary tropical seasonal rainforests is confirmed by Bao et al. (2008, p. 737). Xishuangbanna's primary tropical seasonal rainforests tend to have more biomass than local rubber plantations, as the latter usually have a lower planting density, few or no groundcover, a lower complexity of community hierarchy, and a significantly lower species diversity (Bao et al., 2008, p. 734, 738 and Yang et al., 2005, p. 301).

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

This chapter presents estimates for biomass, litter inputs, exported carbon, soil carbon, soil CO_2 emissions and carbon balance per ha of every land use in the sub-watershed (hereafter watershed), per entire area of every land use, as well as per entire watershed area. The estimates are based on outputs of the LUCIA model (Table 11) that comprise a simulation period of 12 years, namely from 1992 until 2003. The additional model outputs by land use are used for the control of correctness of the model runs.

Table 11 Outputs of the LUCIA model

Outputs at test points	Unit
Biomass	[Mg per ha]
Total carbon in topsoil	[Mg C per ha]
Total carbon in subsoil	[Mg C per ha]
Litter inputs	[Mg per ha]
Soil erosion	[Mg per ha]
Soil CO_2 release	[Mg CO_2 per ha]
Latex export	[Mg per ha]
Average yield per land use	[Mg per ha]
Exported carbon	[Mg C per ha]
Outputs for the entire watershed area	**Unit**
Total biomass	[Mg]
Total soil CO_2 release	[Mg CO_2]
Latex export	[Mg]
Outputs used for control	**Unit**
Water stress	[non-dimensional, 0-1]
Nitrogen constraint	[non-dimensional, 0-1]
Phosphorus constraint	[non-dimensional, 0-1]
Potassium constraint	[non-dimensional, 0-1]
Soil evaporation	[mm]
Topsoil depth	[cm]
Rooting depth	[cm]
Soil loss	[Mg per ha]
Daily latex flow	[Mg per ha]

Additionally, the mentioned outputs per ha are also used for estimating biomass, total soil carbon, soil CO_2 emissions, yield and carbon balance of the entire area of every land use, as well as of the entire watershed area. For this purpose, the outputs, e.g. biomass, are multiplied by the entire area of every land use (Equation 6) and added up for the entire watershed area (Equation 7).

$$\text{Biomass per land use area}_i\ [\text{Mg}] = \text{biomass}_i\ [\text{Mg/ha}] * \text{land use area}_i\ [\text{ha}] \quad (6)$$

$$\text{Biomass of the watershed area}\ [\text{Mg}] = \sum \text{biomass per land use area}_i\ [\text{Mg}] \quad (7)$$

These results are used to calculate the carbon balance. The results by land use area and some results for the watershed area are not simulated by the LUCIA model; they are estimated by the author based on model outputs per ha. They are therefore referred to as "estimated, while those results for the watershed area simulated by LUCIA are referred to as "simulated".

4.2.1 Biomass, Litter Inputs and Carbon Exports

4.2.1.1 Biomass

The total area by land use in 1992 and 2003, in descending order, corresponds to 4,612.3 and 3,181.1 ha for secondary forests, 1,901.4 and 1,880.9 ha for primary forests, 0.0 and 850.9 ha for rubber, 10.7 and 368.4 ha for maize, 116.2 and 349.9 ha for paddy rice, 195.0 ha for grasslands, 34.0 ha for villages, 3.8 and 16.5 ha for tea, and 1.1 and 2.3 ha for orchards (Figure 26).

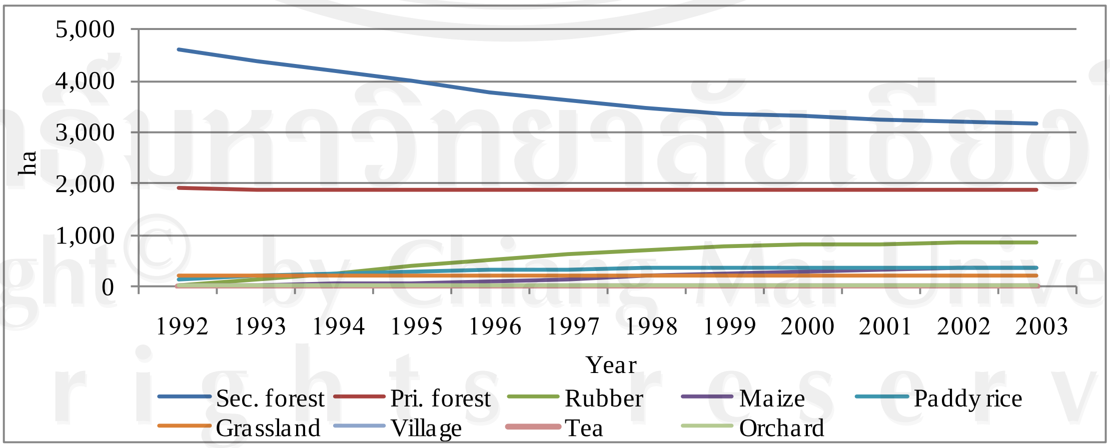


Figure 26 Total area in ha by land use in the sub-watershed, 1992 to 2003

Table 12 shows the total area in ha by land use in the watershed from 1992 until 2003.

Table 12 Total area in ha by land use in the sub-watershed, 1992 to 2003

	Land use area in ha								
Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Village	Tea	Orchard
1992	4,612	1,901	0	11	116	195	34	4	1
1993	4,395	1,894	132	22	189	195	34	8	1
1994	4,206	1,890	250	43	237	195	34	10	1
1995	4,005	1,890	379	69	290	195	34	15	2
1996	3,788	1,886	528	94	327	194	34	16	2
1997	3,617	1,884	641	141	340	194	34	17	2
1998	3,485	1,885	720	194	345	195	34	17	2
1999	3,375	1,885	772	251	347	195	34	17	2
2000	3,304	1,882	808	290	348	195	34	17	2
2001	3,251	1,882	827	319	349	195	34	17	2
2002	3,217	1,882	841	343	349	196	34	17	2
2003	3,181	1,881	851	368	350	196	34	17	2

The average yearly expansion or contraction (-) rate of the total area by land use, in ascending order, corresponds to -130.1 ha for secondary forests, -1.9 ha for primary forests, grasslands and villages remain the same size throughout, 0.1 ha for orchards, 1.2 ha for tea, 21.2 ha for paddy rice, 32.5 ha for maize, and 77.4 ha for rubber (Table 13). Furthermore, the average yearly expansion and contraction rate (-) of the area by land use, in descending order, is 8.1% for maize, 7.0% for rubber, 6.4% for tea, 5.6% for paddy rice, 4.2% for orchards, -0.1% for primary forests, and -3.8% for secondary forests. It could not be confirmed that these rates correspond to the real land use change rates in the sub-watershed, as it was not possible to access accurate information. However, they show a similar tendency to the land use change pattern in the NRWNNR between 1994 and 2004 (Wehner, 2010, p. 14).

Table 13 Average yearly expansion rate in ha and % by land use in the sub-watershed, 1992 to 2003

Unit	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Village	Tea	Orchard
ha	-130.1	-1.9	77.4	32.5	21.2	0.0	0.0	1.2	0.1
%	-3.8	-0.1	7.0	8.1	5.6	0.0	0.0	6.4	4.2

Figure 27 presents the simulated biomass in Mg per ha of the watershed's primary forests, secondary forests at LE and ME (hereafter LME) and at HE, rubber at LME and at HE, grasslands, tea, as well as maize and paddy rice at all elevations (hereafter LMHE). Their biomass carbon contents, in descending order, are 129.19 Mg C per ha for primary forests, 73.89 Mg C per ha for secondary forests, 34.35 Mg C per ha for 11 year-old rubber at LME, 22.55 Mg C per ha for 11 year-old rubber at HE, 16.28 Mg C per ha for grasslands, 14.31 Mg C per ha for orchards/tea, 12.87 Mg C per ha for maize, and 8.42 Mg C per ha for paddy rice. The simulated biomasses correspond to experimental estimates for Xishuangbanna and alternative locations used for calibration and validation of the model (Chapter Five).

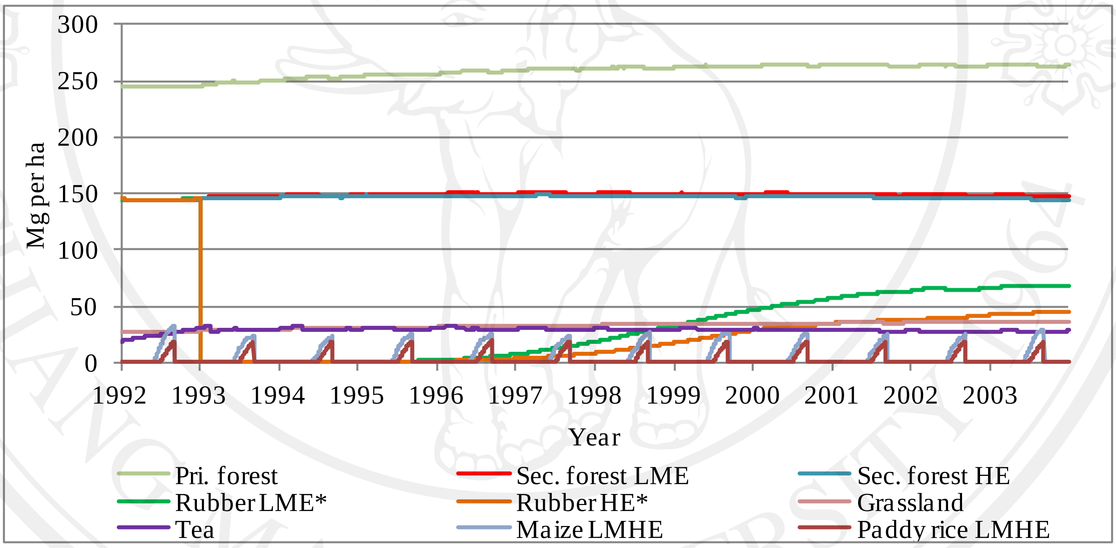


Figure 27 Biomass in Mg per ha of the sub-watershed's land uses, 1992 to 2003
*The sharp change in 1993 corresponds to the transition from sec. forest to rubber plantation

Due to the increase in land use areas (Table 12), total biomass by land use area increases throughout the simulation period in the following land use types. The biomasses of these land uses in 1992 and 2003, in ascending order, reach 18.70 and 56.23 Mg for orchards, 74.82 and 477.99 Mg for tea, 2,120.94 and 6,423.27 Mg for paddy rice (one day before harvest), 5,301.39 and 7,064.68 Mg for grasslands, 353.47 and 10,314.16 Mg for maize (one day before harvest), 0.00 and 42,599.60 Mg for rubber (Figure 28), and 466,358.64 and 496,672.41 Mg for primary forests. Primary forest biomass in the watershed increased despite its decreasing area. Conversely, the biomass of secondary forests decreases from 667,849.88 Mg in 1992 to 464,527.79

Mg in 2003 (Figure 29). Additionally, secondary forest biomass is the highest among all land uses until primary forest biomass surpasses it in 2000.

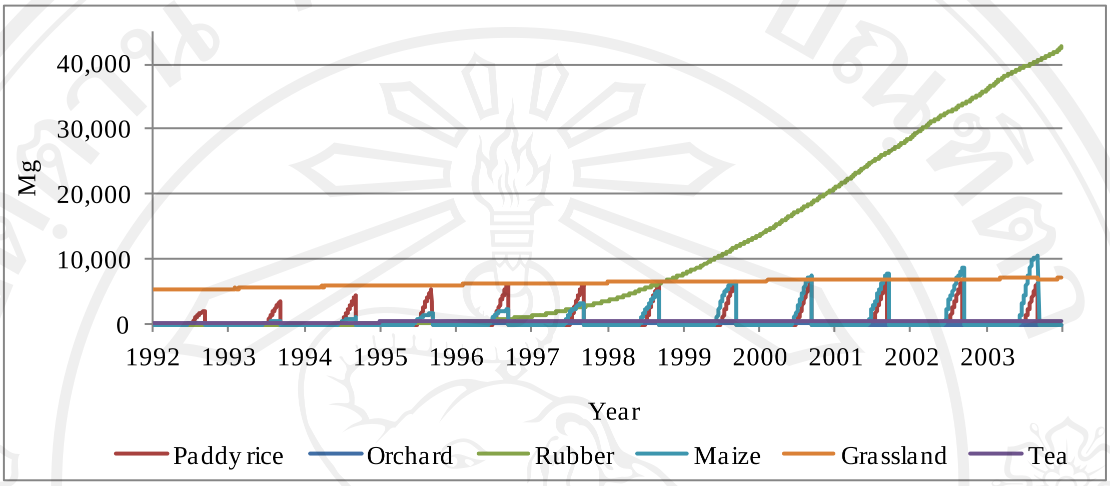


Figure 28 Biomass in Mg by land use area in the sub-watershed, 1992 to 2003

In 1992 and 2003, the estimated watershed's biomass is made up by 58.5% and 45.4% secondary forests, 40.8% and 48.3% primary forests, 0.0% and 3.9% rubber, and by 0.7% and 2.4% of the remaining land uses, respectively (Table 14). This reflects the effects of land use change in the watershed, where mainly secondary forests are replaced in order to expand the agricultural frontier.

Table 14 Biomass in Mg by land use area in the sub-watershed, 1992 and 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1992	667,849.88	466,358.64	0.00	353.47	2,120.94	5,301.39	74.82	18.70
2003	464,527.79	496,672.41	42,599.60	10,314.16	6,423.27	7,064.68	477.99	56.23

Simulated watershed biomass decreases from 1,055,000.00 Mg in 1992 to 913,051.00 Mg in 2003 (one day before paddy rice and maize harvest), while estimated watershed biomass accounts for 1,138,495.39 and 1,025,540.18 Mg (one day before paddy rice and maize harvest) in 1992 and 2003, respectively (Figure 29). The reduction of simulated and estimated biomass throughout the simulation period corresponds to 239,599.00 and 113,941.71 Mg. Furthermore, the yearly watershed biomass reduction slows down at the beginning of 2000 when it seems to reach a temporary steady state. The biomass reduction can be mainly attributed to the replacement of secondary forests with plantations of rubber, maize and paddy rice.

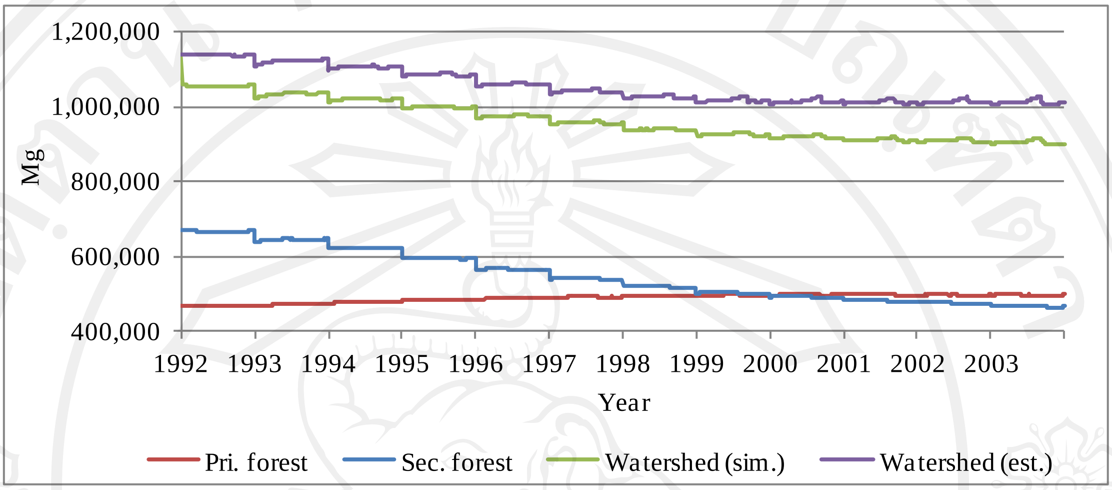


Figure 29 Biomass in Mg by forest type area and sub-watershed, 1992 to 2003

Discrepancies between simulated and estimated biomass can be partly attributed to the model's biomass growth restriction in pixels where, e.g., soil deposition and soil erosion are too high, among other factors. This was observed for some test points. However, such pixels are omitted for calculating estimated biomass, as it is a multiplication of the biomass of each land use type in Mg per ha by its respective land use area and added up for the entire watershed (Equation 6 and 7). As a result, estimated biomass can be higher than simulated biomass.

4.2.1.2 Litter Inputs and Carbon Exports

The average yearly litter inputs by land use per ha, in descending order, correspond to 4.8393 Mg C per ha for maize, 3.1795 Mg C per ha for paddy rice, 0.0174 Mg C per ha for grasslands, 0.0160 Mg C per ha for orchards/tea, 0.0122 Mg C per ha for primary forests, and 0.0076 Mg C per ha for secondary forests. Moreover, the watershed's lowest litter inputs are 0.0019 Mg C per ha from rubber at LME, and 0.0013 Mg C per ha from rubber at HE (Figure 30). The litter input values for perennial vegetation were underestimated by the LUCIA model as discussed further in Chapter Six.

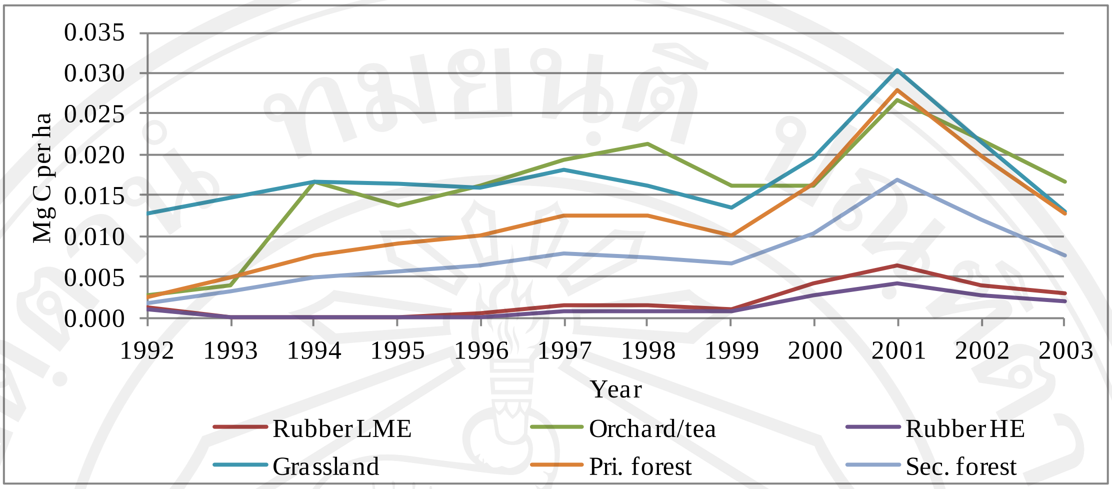


Figure 30 Litter inputs in Mg C per ha by land use of the sub-watershed, 1992 to 2003

The litter inputs by land use area overall increase throughout the simulation period, showing a sharp increase from 1999 until 2001, which is followed by a sharp decrease until 2003. The cumulative litter inputs by the end of 2003, in descending order, are highest for paddy rice, followed by maize, secondary forests, primary forests, grasslands, rubber, tea, and finally orchards (Table 15). Furthermore, the entire watershed's litter inputs increase from 438.37 Mg C in 1992 to 3,038.57 Mg C in 2003.

Table 15 Cumulative litter inputs in Mg C by land use area in the sub-watershed, 1992 to 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1992-2003	320.17	275.70	9.45	10,343.59	11,435.59	40.73	3.02	0.36

Moreover, average yearly carbon exports[13] by land use per ha are higher than average yearly litter inputs by land use per ha. In descending order, they are 4.71 Mg C per ha for maize, 2.43 Mg C per ha for paddy rice, 1.02 Mg C per ha for orchards/tea, 0.30 Mg C per ha for primary forests, 0.28 Mg C per ha for secondary forests, and 0.24 Mg C per ha for grasslands (Figure 31). The watershed's lowest carbon exports correspond to 0.23 Mg C per ha for rubber at LME, and 0.22 Mg C per ha at HE. Furthermore, once rubber plantations are tapped, their carbon exports additionally increase in the form of latex exports. Rubber at HE is not tappable

[13] Carbon exports include the carbon in harvest and in fodder, recollected surface metabolic carbon, and recollected surface structural carbon.

throughout the simulation period; therefore, there is no latex export. However, rubber at LME is tapped and has latex exports of 0.98 Mg C per ha in 2001, 3.15 Mg C per ha in 2002, and 2.75 Mg C per ha in 2003. The tapping value for 2001 corresponds to the experimental estimates for Xishuangbanna (Jia, 2006). The values for 2002 and 2003 are overestimations of the LUCIA model.

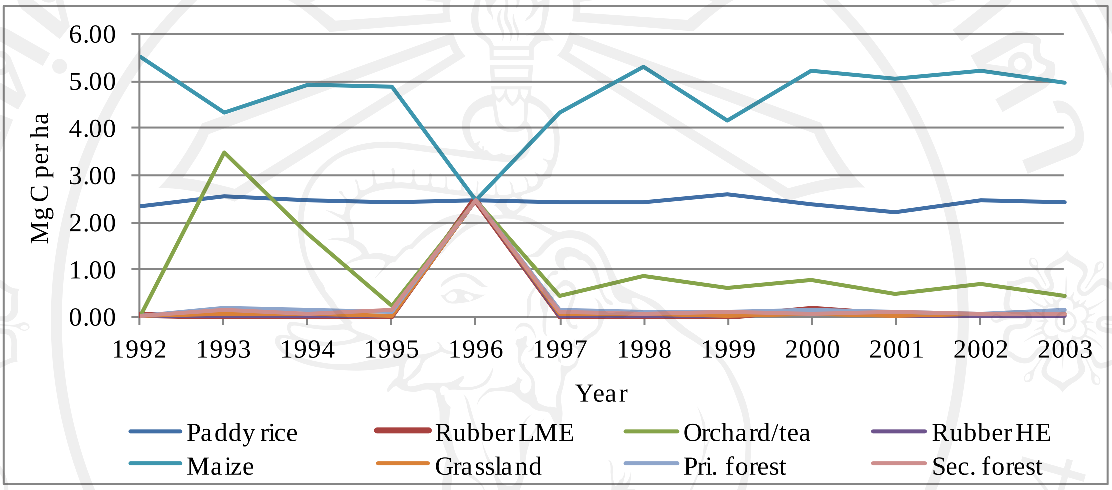


Figure 31 Carbon exports in Mg C per ha by land use of the sub-watershed, 1992 to 2003

The carbon exports of the areas under maize and rubber increase over the simulation period. Paddy rice exports increase and slow down in 1999, while the exports of secondary and primary forests and tea overall decrease. Moreover, grasslands and orchards show mostly constant carbon exports. The cumulative exported carbon by the end of 2003, in descending order, is highest for maize, followed by paddy rice, secondary forests, primary forests, tea, rubber, grasslands, and finally orchards (Table 16). Additionally, the entire watershed's exported carbon increases from 418.27 Mg C in 1992 to 3,105.73 Mg C in 2003.

Table 16 Cumulative carbon exports in Mg C by land use area in the sub-watershed, 1992 to 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1992-2003	3,341.19	2,416.32	109.30	10,572.58	8,737.58	84.44	141.67	16.76

4.2.2 Soil Carbon

This section refers to the total carbon in the topsoil and subsoil of all land uses in the watershed throughout the simulation period. Along with rubber and orchards/tea, paddy rice has relatively low topsoil carbon (Figure 32). The low topsoil carbon of orchards/tea and paddy rice is due to the lower soil organic carbon content of the Acrisols and Gleysols on which they grow, respectively (Appendix B: Soil). These have a much lower soil organic carbon content than the Acrisols under rubber, and Ferralsols under the remaining land uses. Paddy rice is the only land use that shows an increase - from 16.66 to 22.70 Mg C per ha - in topsoil carbon throughout the simulation period, that represents an increase by 25.6%. The topsoil carbon reduction of orchards/tea is by 10.03 Mg C per ha (-67.2%), and the one of rubber by 11.14 Mg C per ha (-80.6%).

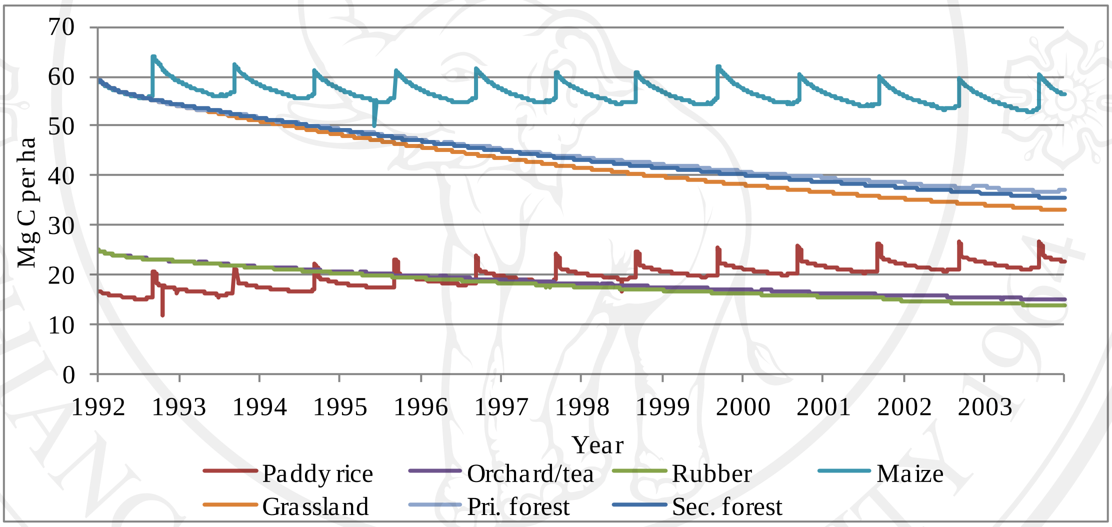


Figure 32 Carbon in topsoil in Mg C per ha for every land use in the sub-watershed (adjusted values[14]), 1992 to 2003

Furthermore, after paddy rice topsoil carbon surpasses that of rubber and orchards/tea in 1998, rubber has the lowest topsoil carbon among all land uses, followed by orchards/tea. Primary forests, secondary forests and grasslands have some of the highest topsoil carbon contents, which are reduced by 22.46 Mg C per ha (-60.8%), 23.94 Mg C per ha (-67.5%), and 26.38 Mg C per ha (-79.8%), respectively (Table 17). The drastic decreases in soil carbon can be due to the model's underestimated litter inputs for perennial vegetation (Chapter 6.1.2). Among all assessed land uses, maize has the overall highest topsoil carbon, showing a decrease of only 2.95 Mg C per ha (-5.2%).

[14] Occasionally topsoil carbon values drastically increased or decreased for one to three days; therefore, these values were replaced with averages of the previous day and subsequent day.

Table 17 Topsoil carbon contents in Mg C per ha (adjusted values), 1992 and 2003

Year	Secondary forest	Primary forest	Rubber LME	Rubber HE	Maize	Paddy rice	Grassland	Orchard/tea
1992	59.42	59.42	24.96	24.96	59.21	16.66	59.42	24.96
2003	35.48	36.96	13.82	13.82	56.26	22.70	33.04	14.93

The subsoil carbon under all evaluated land uses decreases throughout the simulation period (Figure 33). With 108.17 and 70.64 Mg C per ha in 1992 and 2003, respectively, paddy rice has the highest subsoil carbon among all land uses. The carbon content of all other land uses is similar, it ranges from between 79.17 and 83.38 Mg C per ha in 1992 to between 53.74 and 57.35 Mg C per ha in 2003. Furthermore, rubber has the overall lowest subsoil carbon with 79.17 Mg C per in 1992 and 53.74 Mg C per ha in 2003. Additionally, the total soil (topsoil+subsoil) carbon of every land use per ha, including paddy rice, decreases throughout the simulation period.

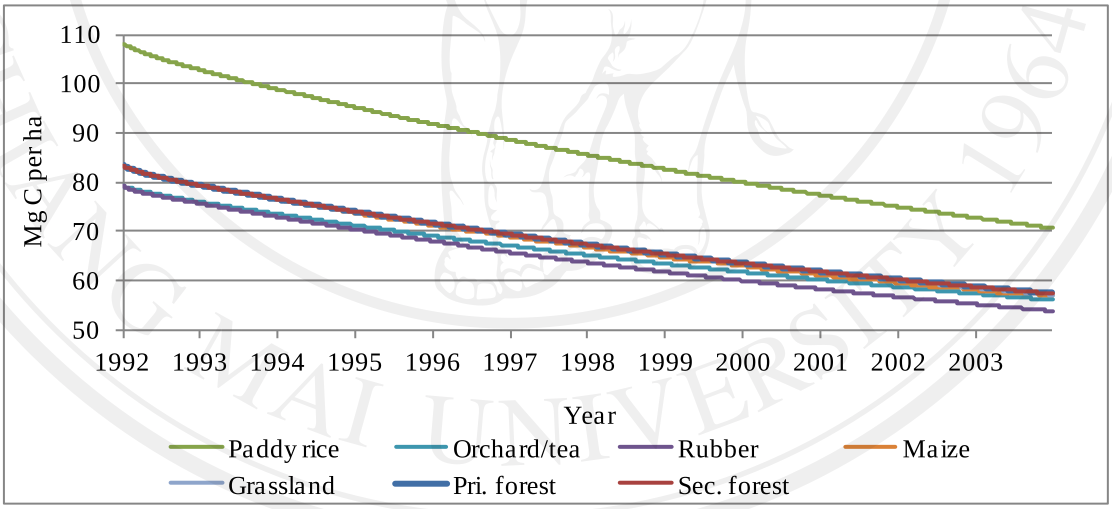


Figure 33 Carbon in subsoil in Mg C per ha for every land use in the sub-watershed, 1992 to 2003

Total soil carbon of the areas under grasslands, and primary and secondary forests decreases throughout the simulation period (Figure 34). Conversely, total soil carbon of the area under maize increases. Total soil carbon increases during a part of the simulation period before it begins to drop in 1996 for orchards, in 1998 for paddy rice and tea, and in 2002 for rubber. Total soil carbon by land use area in 2003, in descending order, is higher in secondary forests with 295,057.95 Mg C per ha, 177,390.34 Mg C per ha in primary forests, 63,243.89 Mg C per ha in rubber, 41,601.85 Mg C per ha in maize, 32,672.26 in paddy rice, followed by grasslands, tea, and orchards (Table 18).

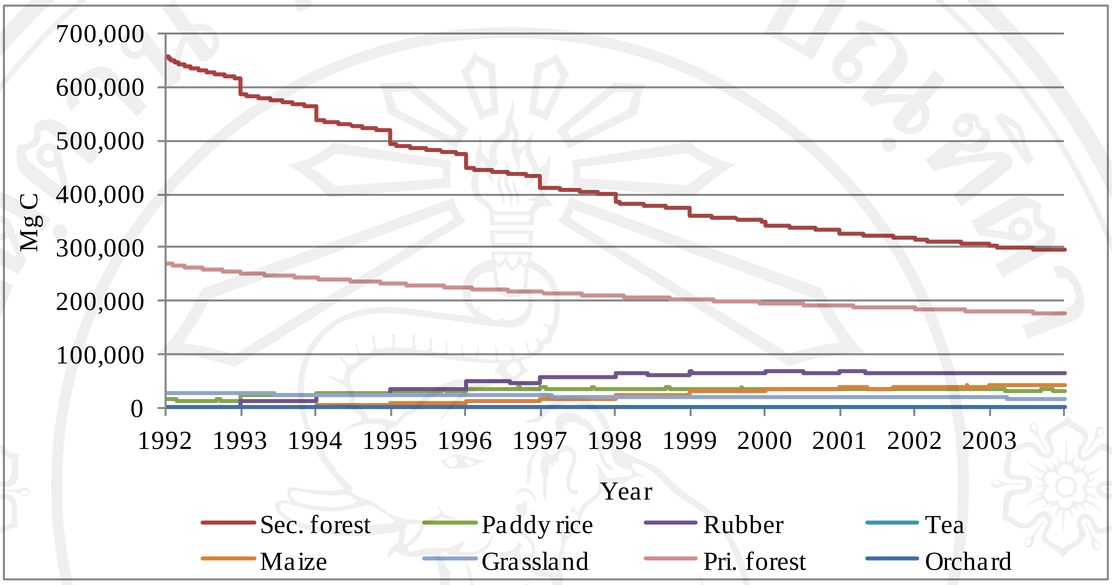


Figure 34 Total soil carbon in Mg C by land use area in the sub-watershed (adjusted values), 1992 to 2003

Table 18 shows the total soil carbon by land use area in the sub-watershed in 1992 and 2003.

Table 18 Total soil carbon in Mg C by land use area in the sub-watershed (adjusted values), 1992 and 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1992	658,601.44	271,466.03	0.00	1,568.46	14,480.83	27,846.35	416.55	104.14
2003	295,057.95	177,390.34	63,243.89	41,601.85	32,672.26	17,658.95	1,205.32	141.80

In 1992 and 2003, the watershed's total soil carbon is made up by 67.6% and 46.9% secondary forests, 27.9% and 28.2% primary forests, 0.0% and 10.1% rubber, and by 4.5% and 14.8% of the remaining land uses, respectively. In addition, by the end of the simulation period, the cumulative soil erosion by land use area, in descending order, reaches 349,853.76 Mg soil for maize, 176,464.96 Mg soil for rubber, 74,232.57 Mg soil for paddy rice, 3.93 Mg soil for secondary forests, 0.31 Mg soil for primary forests, 0.06 Mg soil for tea, and 0.03 Mg soil for grasslands.

4.2.3 Soil Carbon Dioxide Emissions

This section presents the soil carbon dioxide emissions of all land uses in the watershed throughout the entire simulation period. The average daily soil CO_2 emissions per ha (1993 to 2003), in descending order, are highest in primary forests, followed by secondary forests, orchards/tea, maize, paddy rice, and grasslands (Figure 35; Table 19). Among the studied land uses, rubber plantations have the watershed's lowest soil CO_2 emissions with 0.011 Mg CO_2 per ha at LME, and 0.009 Mg CO_2 per ha at HE. Moreover, all land uses show low daily CO_2 emissions at the end and beginning of every year, which coincide with the dry season in Xishuangbanna. Accordingly, the high emissions throughout the remaining part of the year (omitting the sharp peaks caused at maize harvest) coincide with the rainy season.

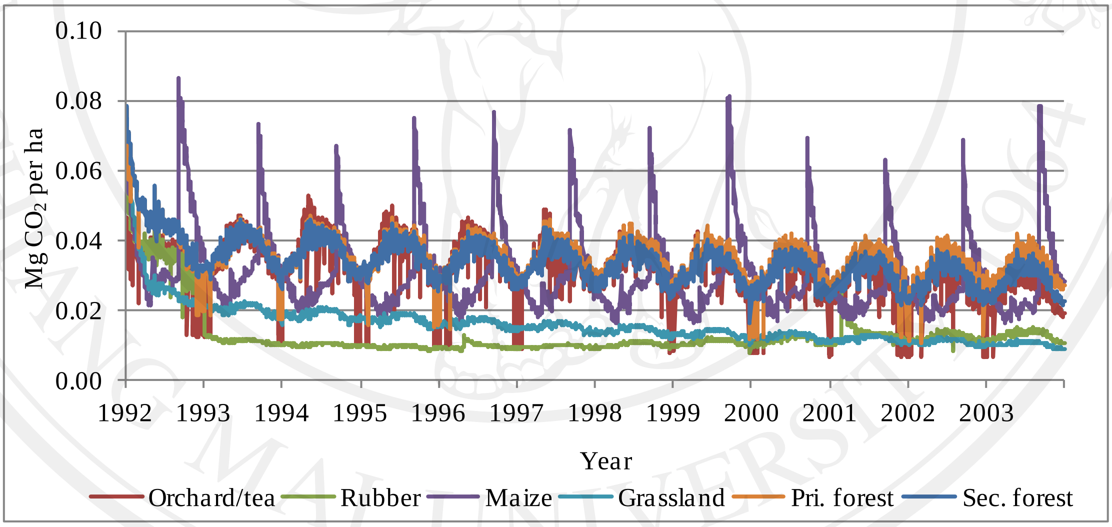


Figure 35 Daily soil CO_2 release in Mg CO_2 per ha by land use in the sub-watershed, 1992 to 2003

Furthermore, the average yearly cumulative soil CO_2 emissions by land use per ha (1993 to 2003) decrease throughout the simulation period, except for rubber at LME that shows an increase in emissions. As a means of comparison with rubber at LME, the average yearly cumulative soil CO_2 emissions by land use per ha, in descending order, are 214.3% higher in primary forests than in rubber at LME, 198.5% higher in secondary forests, 187.5% higher in orchards/tea, 169.9% higher in maize, 131.1% higher in paddy rice, and 33.1% higher in grasslands (Table 19).

Table 19 Mean daily and mean yearly cumulative soil CO_2 emissions in Mg CO_2 per ha, 1993 to 2003

Time step	Secondary forest	Primary forest	Rubber LME	Rubber HE	Maize	Paddy rice	Grassland	Orchard /tea
Daily	0.033	0.034	0.011	0.009	0.030	0.025	0.015	0.031
Yearly	11.91	12.54	3.99	3.33	10.77	9.22	5.31	11.47

The land use areas that expand throughout the simulation period show an increase in CO_2 emissions, such as rubber and maize (Figure 36). At the same time, the contracting land use areas present decreasing CO_2 emissions, like secondary forests (Figure 37). Moreover, the paddy rice's yearly sharp peaks of CO_2 emissions coincide with its harvest around day 250 of every year.

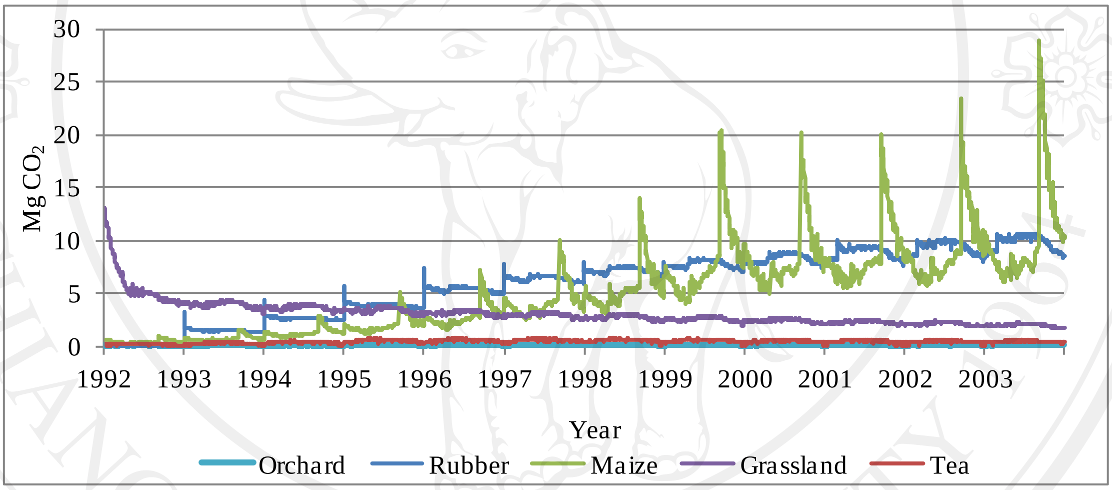


Figure 36 Daily soil CO_2 release in Mg CO_2 by land use area in the sub-watershed, 1992 to 2003 I

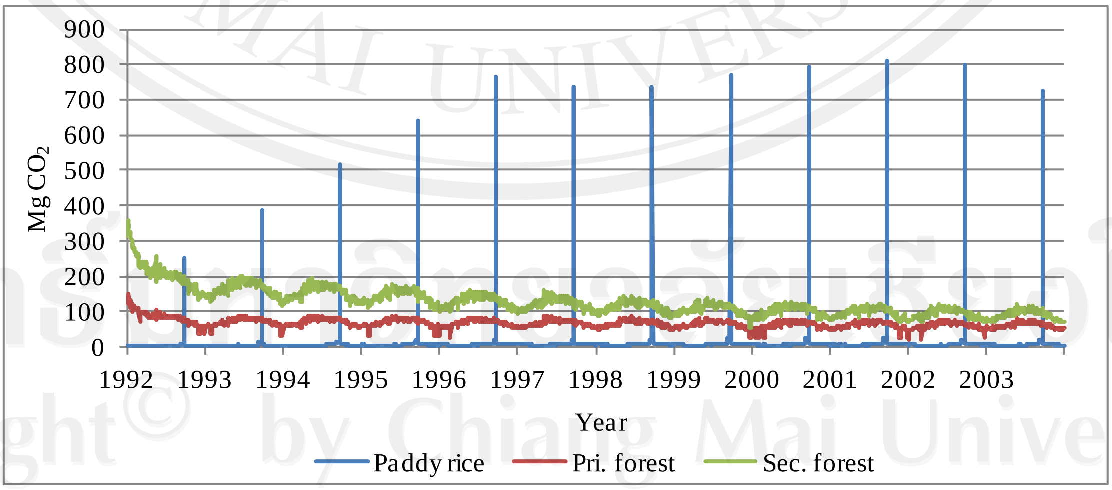


Figure 37 Daily soil CO_2 release in Mg CO_2 by land use area in the sub-watershed, 1992 to 2003 II

Additionally, the yearly soil CO_2 emissions by land use area in 2003, in descending order, are 32,973.17 Mg CO_2 for secondary forests, 22,181.97 Mg CO_2 for primary forests, 3,776.10 Mg CO_2 for maize, 3,573.64 Mg CO_2 for rubber, 2,897.33 Mg CO_2 for paddy rice, followed by grasslands, tea, and finally orchards (Table 20).

Table 20 Yearly soil CO_2 emissions in Mg CO_2 by land use area, 1994 and 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1994	56,164.87	25,623.33	969.47	471.46	2,230.85	1,327.85	135.05	13.50
2003	32,973.17	22,181.97	3,573.64	3,776.10	2,897.33	731.39	155.15	18.25

In 1994 and 2003, the watershed's yearly soil CO_2 emissions are composed of 64.6% and 49.7% secondary forests, 29.5% and 33.5% primary forests, 1.1% and 5.4% rubber, and of 4.8% and 11.4% of the remaining land uses, respectively. Moreover, by the end of the simulation period, the cumulative soil CO_2 emissions by land use area, in descending order, correspond to 555,093.74 Mg CO_2 for secondary forests, 290,975.52 Mg CO_2 for primary forests, 32,456.59 Mg CO_2 for paddy rice, 25,893.14 Mg CO_2 for rubber, 22,500.18 Mg CO_2 for maize, followed by grasslands, tea, and orchards (Table 21).

Table 21 Cumulative soil CO_2 emissions in Mg CO_2 by land use area, 1992 to 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1992 - 2003	555,093.74	290,975.52	25,893.14	22,500.18	32,456.59	13,501.61	1,945.58	238.40

The daily soil CO_2 emissions of the watershed decrease yearly throughout the simulation period (Figure 38).

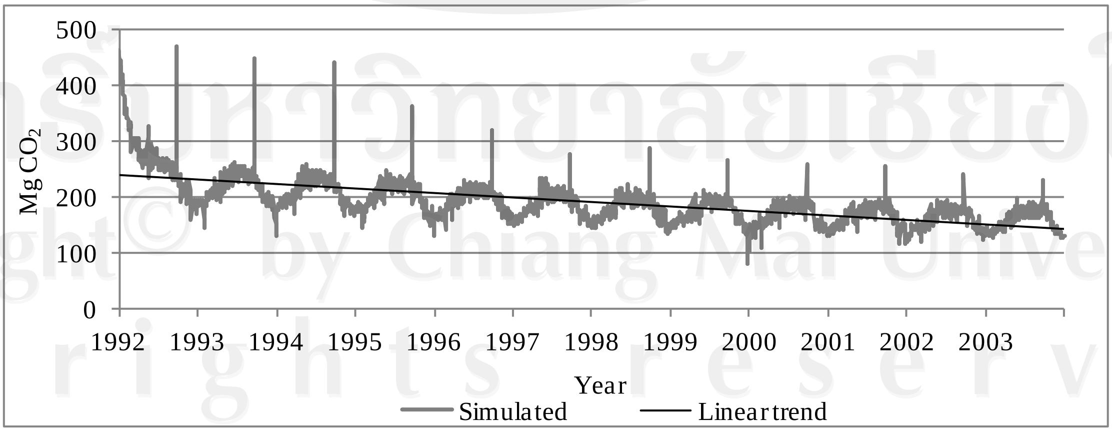


Figure 38 Daily soil CO_2 release in Mg CO_2 of the sub-watershed, 1992 to 2003

The yearly cumulative soil CO_2 emissions of the watershed decrease as well. The highest simulated emissions reach 97,908.19 Mg CO_2 in 1992, while the lowest emissions reach 58,184.69 Mg CO_2 in 2003 (Table 22). The estimated emissions account for 110,780.14 and 66,307.01 Mg CO_2 in 1992 and 2003, respectively. The watershed's simulated and estimated carbon emissions decrease throughout the simulation period by 39,723.50 and 44,473.13 Mg CO_2, correspondingly.

Table 22 Simulated (sim.) and estimated (est.) yearly cumulative soil CO_2 emissions in Mg CO_2 of the sub-watershed, 1992 to 2003

Year	Mg CO_2 (sim.)	Mg CO_2 (est.)	Year	Mg CO_2 (sim.)	Mg CO_2 (est.)
1992	97,908.19	110,780.14	1998	65,965.52	74,111.50
1993	79,457.03	89,618.90	1999	63,326.96	71,579.56
1994	77,501.52	86,936.37	2000	61,611.61	69,439.03
1995	74,029.56	83,082.35	2001	60,501.01	68,481.48
1996	70,749.48	79,188.08	2002	58,683.38	66,479.37
1997	68,182.71	76,600.97	2003	58,184.69	66,307.01

4.2.4 Carbon Balance

The carbon balance is the difference between the net change in carbon stocks (e.g. biomass and soil carbon) in the studied system and/or carbon added to it and the carbon that is removed (e.g. harvesting and latex export) from it in a specific time frame, normally yearly (Aalde et al., 2006 and Bockel et al., 2011, p. 3). This study uses the outputs from the LUCIA model for estimating the carbon balance of the sub-watershed. Carbon balance is estimated for every land use on a hectare basis (Equation 8 and 9), for every land use area (Equation 10), as well as for the entire watershed (Equation 11). It is estimated for every year, as well as for the entire simulation period. The latter is estimated by summing up the yearly carbon balances. Furthermore, the calculations are carried out in Mg C; the results are converted to Mg CO_2, as carbon balance is normally reported in Mg CO_2.

The carbon balances per ha for perennial woody land uses are calculated as follows:

$$C_{balance\ i}\ [MgCO_2/ha] = B_i + C_{topsoil\ i} + C_{subsoil\ i} - Y_i - La_{export\ i}, \qquad (8)$$

where $C_{balance}$ is carbon balance, B is biomass net change, $C_{topsoil}$ is the net change of total carbon in topsoil, $C_{subsoil}$ is the net change of total carbon in subsoil, Y is yield, and La_{export} is the cumulative latex that is removed from rubber trees.

The carbon balances per ha for annual crops are calculated as:

$$C_{balance\ i}\ [MgCO_2/ha] = C_{topsoil\ i} + C_{subsoil\ i}, \quad (9)$$

as it is assumed that the biomass of one year is equivalent to biomass removed due to harvesting and mortality in that same year, resulting in no biomass accumulation (Aalde et al., 2006).

The carbon balance per land use area of perennials and annual crops is computed as:

$$C_{balance\_land\_use\_area\ i}\ [Mg\ CO_2] = C_{balance\ i}\ [MgCO_2/ha] * \text{land use area [ha]}. \quad (10)$$

The carbon balance for the watershed is calculated as:

$$C_{balance\_watershed}\ [Mg\ CO_2] = \sum C_{balance\_land\_use\_area\ i} \quad (11)$$

The yearly carbon balances per ha of all land uses are mostly negative throughout the simulation period (Figure 39). However, rubber at LME shows a positive balance between 1996 and 2001, and rubber at HE between 1997 and 2000 and in 2002. Moreover, rubber at LME and HE have the overall least negative carbon balances per ha. Maize, orchards/tea and paddy rice follow with carbon balances that are less negative than those of grasslands and forests. Furthermore, the balance of the land uses becomes overall less negative as 2003 is approached, except for rubber at LME and at HE that show more negative balances towards the end of the simulation period.

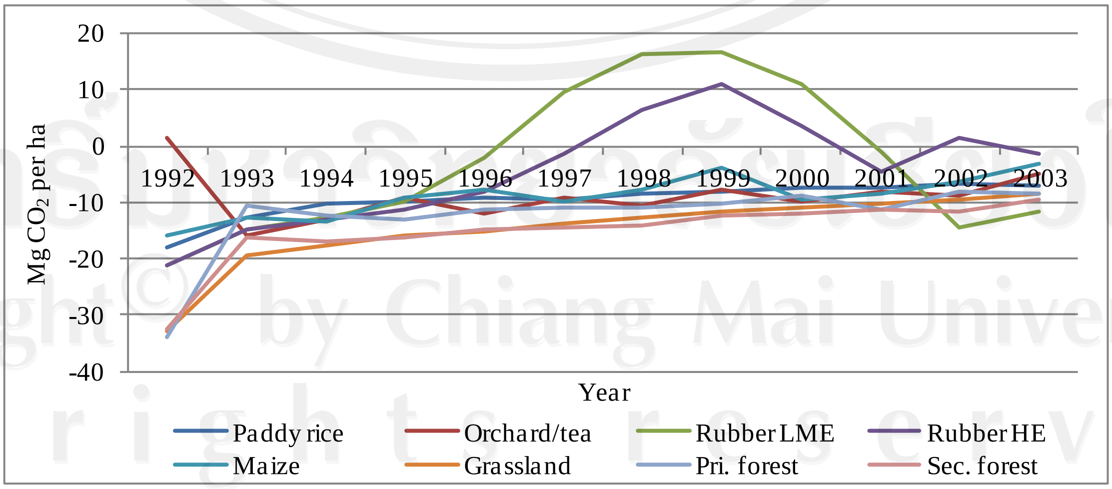


Figure 39 Carbon balance in Mg CO_2 per ha of the land uses in the sub-watershed, 1992 to 2003

The carbon balance in 2001, in descending order, corresponds to -0.84 Mg CO_2 per ha for rubber at LME, -4.51 Mg CO_2 per ha for rubber at HE, -7.33 Mg CO_2 per ha for paddy rice, -7.98 Mg CO_2 per ha for orchards/tea, -8.31 Mg CO_2 per ha for maize, -10.26 Mg CO_2 per ha for grasslands, -11.26 Mg CO_2 per ha for secondary forests, and -11.45 Mg CO_2 per ha for primary forests (Table 23). The balances of rubber at LME in 2002 and 2003 are attributed to the LUCIA model's overestimation of latex exports.

Table 23 Carbon balance in Mg CO_2 per ha of the land uses in the sub-watershed, 1994 and 2001

Time step	Secondary forest	Primary forest	Rubber LME	Rubber HE	Maize	Paddy rice	Grassland	Orchard /tea
1994	-16.94	-12.46	-12.78	-12.97	-13.30	-10.29	-17.74	-13.07
2001	-11.26	-11.45	-0.84	-4.51	-8.31	-7.33	-10.26	-7.98

The carbon balance per ha for the entire simulation period is negative for all land uses (Figure 40). Their carbon balance, in ascending order, is -181.92 Mg CO_2 per ha for secondary forests, -178.75 Mg CO_2 per ha for grasslands, -149.98 Mg CO_2 per ha for primary forests, -114.78 Mg CO_2 per ha for paddy rice, -107.77 Mg CO_2 per ha for orchards/tea, -107.16 Mg CO_2 per ha for maize, -55.22 Mg CO_2 per ha for rubber at HE, and -34.10 Mg CO_2 per ha for rubber at LME.

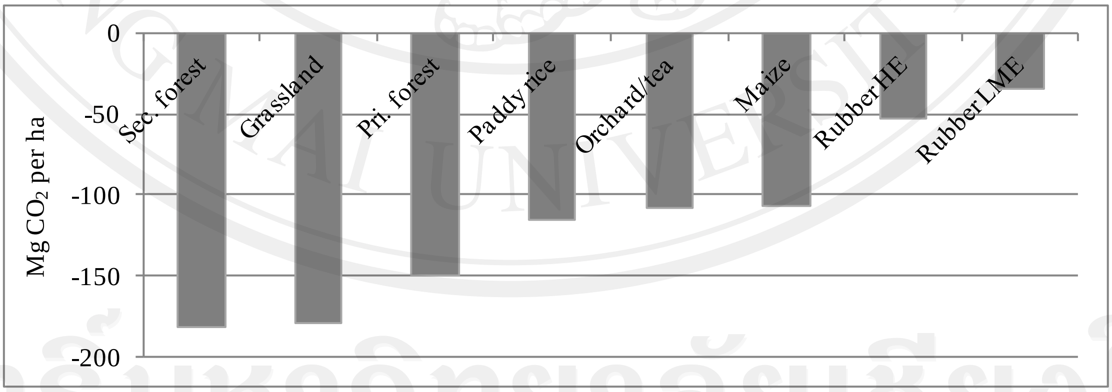


Figure 40 Cumulative carbon balance in Mg CO_2 per ha of the land uses in the sub-watershed, 1992 to 2003

The yearly carbon balance for all land use areas is overall negative and becomes overall less negative as 2003 is approached (Figure 41). The carbon balance by land use area in 2003, in descending order, is the least negative for orchards, followed by tea, maize, grasslands, paddy rice with -2,421.01 Mg CO_2, rubber with -10,002.91 Mg

CO_2, primary forests with -15,706.93 Mg CO_2, and secondary forests with -32,315.39 Mg CO_2 (Table 24).

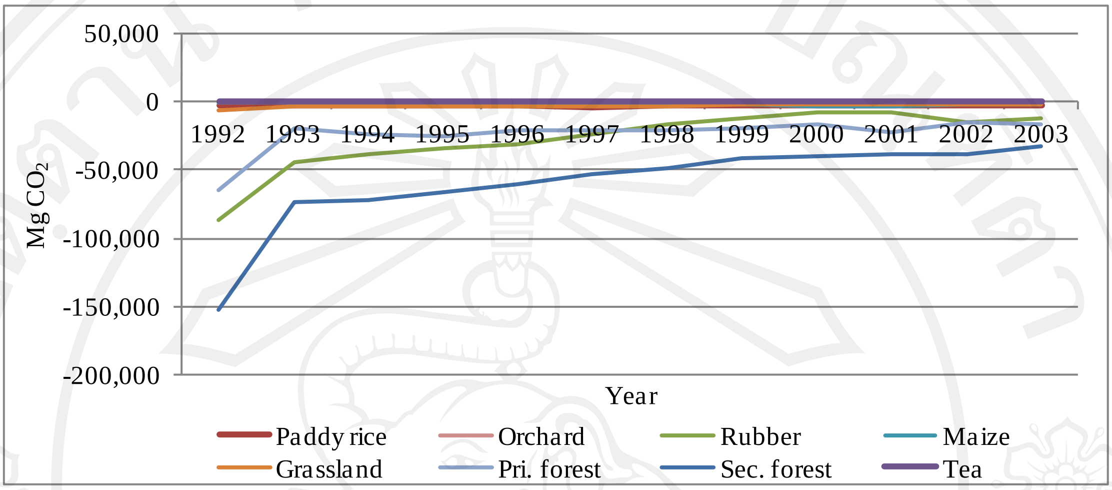


Figure 41 Yearly carbon balance in Mg CO_2 by land use area in the sub-watershed, 1992 to 2003

In addition, the cumulative carbon balance by land use area for the entire simulation period, in descending order, is the least negative for orchards, followed by tea, maize, paddy rice, grasslands, primary forests with -283,358.34 Mg CO_2, rubber with -326,378.68 Mg CO_2, and secondary forests with -714,435.43 Mg CO_2 (Table 24).

Table 24 Yearly and cumulative carbon balance in Mg CO_2 by land use area in the sub-watershed, 1992 to 2003

Year	Secondary forest	Primary forest	Rubber	Maize	Paddy rice	Grassland	Tea	Orchard
1994	-71,508.47	-23,555.29	-38,661.99	-571.92	-2,439.63	-3,458.53	-130.70	-13.07
2003	-32,315.39	-15,706.93	-10,002.91	-1,183.50	-2,421.01	-1,677.63	-84.02	-9.88
1992-2003	-714,435.43	-283,358.34	-326,378.68	-14,944.61	-31,751.93	-34,845.77	-1,585.13	-187.98

Furthermore, in 1994 and 2003, the watershed's carbon balance is composed of 51.0% and 49.4% secondary forests, 16.8% and 24.0% primary forests, 27.5% and 15.3% rubber, and of 4.7% and 11.3% of the remaining land uses, respectively. The watershed's yearly carbon balance is negative over the simulation period (Figure 42), and becomes less negative with every year. The balance is -140,339.60 and -65,401.27 Mg CO_2 in 1994 and 2003, respectively. Furthermore, the balance for the entire simulation is -1,407,487.87 Mg CO_2.

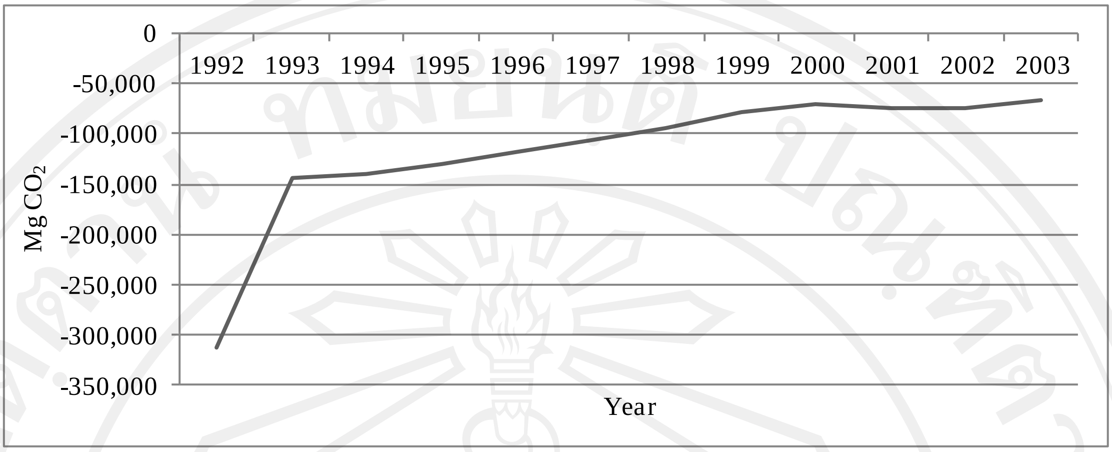


Figure 42 Carbon balance in Mg CO_2 of the sub-watershed, 1992 to 2003