CHAPTER 2

LITERATURE REVIEW

2.1 The Naban River Watershed National Nature Reserve

The Naban River Watershed National Nature Reserve is located in Jinghong County in the Dai Autonomous Prefecture of Xishuangbanna that lies in Yunnan Province, southwest China, and borders Myanmar and Laos (Figure 9). Xishuangbanna is located between latitude 21°08 and 22°36'N and longitude 99°56 and 101°50'E (Cao et al., 2006, p. 306), in which the NRWNNR lies exactly in latitude 22°04 to 22°17'N and longitude 100°32 to 100°44'E (Mo et al., 2011, p. 1833).

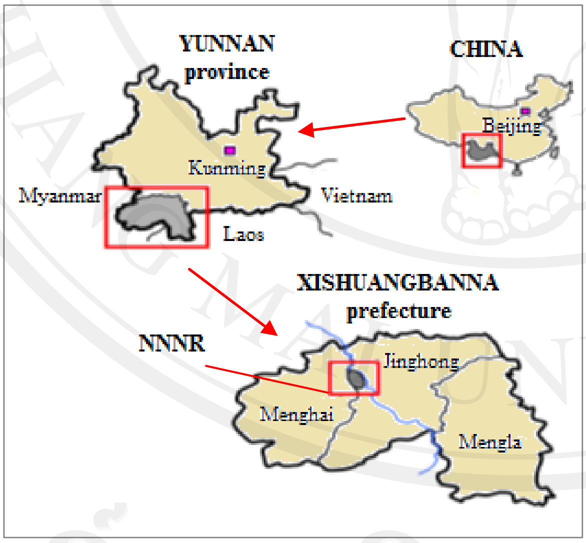

Figure 1 Location of the NRWNNR (adapted from Leshem et al., 2010, p. 1106)

In 1979, the Naban River Watershed was selected in order to protect its fauna, changing its status to Naban River Watershed Nature Reserve in 1991, and becoming the Naban River Watershed National Nature Reserve in 2000 (Mo et al., 2011, p. 1833-1834). Agriculture in the NRWNNR is carried out according to the Man and Biosphere Programme of UNESCO (LILAC). This program targets the economic, ecological and social dimensions of biodiversity loss in order to decrease it; and aims at improving the relationship between economic development and ecological sustainability in a socially suitable way (UNESCO).

As a result, the NRWNNR was divided into three different zones to differentiate between a core zone – 3,900 ha, where extractive activities are not allowed; a buffer zone – 5,800 ha, where agricultural activities are restricted; and an experimental zone – 11,400 ha, where agriculture is carried out with less restrictions (Figure 10; Mo et al., 2011, p. 1833 and LILAC).

The NRWNNR lies on the Mekong River and has a total area of 267 km², which makes 13.9% of Xishuangbanna (Langenberger et al., 2010, p. 10 and Bao et al., 2008, p. 735). Around 95% of Xishuangbanna's area is hilly and mountainous. The NRWNNR's elevation is between 500 and 2304 m.a.s.l. and is highest to the west. Steep slopes can be found from 539 m upwards (Li et al., 2008, p. 17 and Guardiola Claramonte et al., 2010, p. 4). About 90% of the NRWNNR's total area lies between 600 and 1500 m (Langenberger et al., 2010, p. 10). Furthermore, 33% of the total area lies below 1000 m, while 67% lies above 1000 m (Cotter, 2011, p. 44).

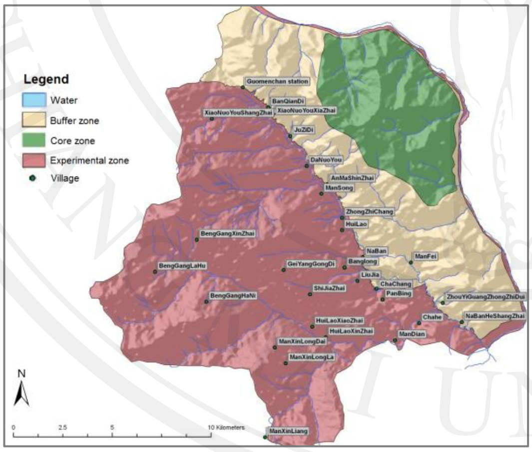

Figure 2 Zonation and settlements in the NRWNNR (Cotter, 2011, p. 6)

The reserve has 30 villages (Figure 10), and is inhabited by 5,564 persons (WWF, 2009) from six ethnic groups, Lahu (50%), Hani (24%), Dai (11%), Yu (below 4%), and Bulang (below 4%). Most people in the reserve rely on agriculture for their subsistence and income generation. Rubber is the most important cash crop below 1000 m (Wehner, 2007, p. 3), covering about 10% of the entire reserve in 2006 and 2007 (Cotter, 2011, p. 48).

Rubber has shown an increasing expansion rate in Xishuangbanna since the 1970s, and was introduced to the NRWNNR in the 1980s (Fox et al., 2009 and Tang et al., 2009, p. 26). Rubber expansion in the area is related to the Chinese Government's efforts of promoting upland farmers to use swiddening land to plant rubber under 700 m, which was followed by a poverty reduction campaign based on the cultivation of rubber on sloping areas. Additionally, in 2003, the Government launched a new "Grain for Green" campaign, giving grain and cash to farmers that plant forest cover on degraded slopes, including rubber, which is classified as a forest species in China (Fox et al., 2009).

The Government's intervention in rubber expansion has been accompanied by the Chinese (1976 to 1990) and the world[1] (2002 until present) markets' overall increasing rubber prices (Figure 11; Fox et al., 2011, p. 14; Sturgeon, 2011; FAOSTAT and Index Mundi). A number of rubber farmers have been able to increase their annual income by up to €3,581[2] per ha (Cotter, 2011, p. 4). However, besides the economic benefits, rubber plantations may have a number of impacts on ecosystem services, such as on carbon sequestration potential (Cotter et al., 2009, p. 10 and Ziegler et al., 2009, p. 1024), creating the need to evaluate these. Therefore, this chapter discusses the properties of the NRWNNR relevant to assess the area's carbon sequestration potential and CO_2 emissions, such as climate, soils, biodiversity, ecosystem services, and land use.

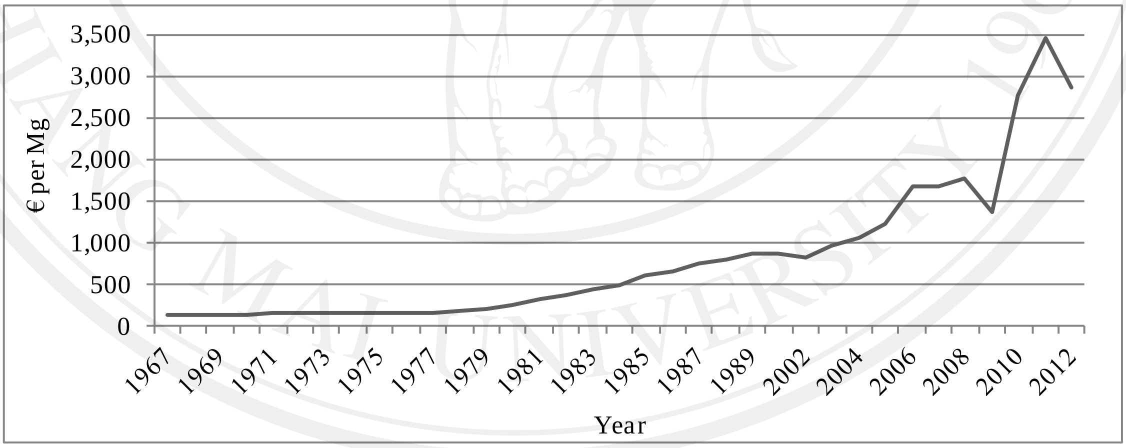

Figure 3 Chinese price of natural rubber in €[3] per Mg, 1967 to 1990 (FAOSTAT), and world price of natural rubber in € per Mg, 2002 to first half of 2012 (Index Mundi)

2.1.1 Climate

Xishuangbanna is located in the tropics, and has an equatorial savannah climate with dry winter and hot summer (category "Aw"[4]; Kottek et al., 2006, p. 260). The

[1] China joined the WTO in December 2001, and since then follows the world price of natural rubber.
[2] 1 EUR = 8.38 CNY: 03.04.2012
[3] 1 EUR = 8.38 CNY: 03.04.2012
[4] Criteria: $T_{min} \geq +18°$ C and $P_{min} < 60$ mm in winter

climatic data presented in this section are from the meteorological station of Jinghong city (21°52'N and 101°04'E), which is located 20 km away from the study site (Zhang et al., 1995, p. 230 and Cotter, 2011, p. 32), and at an elevation of 579 m (meteorological data are validated against 555 m). The area's climatic factors that influence rubber biomass development and latex yield the most are described below, i.e. rainfall, temperature, atmospheric humidity, sunlight, and wind velocity (Liu et al., 2010, p. 381).

Xishuangbanna has a climate that is characterized by a rainy and a dry season. The mean monthly precipitation in Jinghong is similar during the dry season (November until April), and varies during the rainy season (May until October; Figure 12). The mean annual precipitation is of 1166 mm, and can range between ca. 1100 and 1700 mm. About 85% of it occurs in the rainy season (Wikipedia: Jinghong; Mo et al., 2011, p. 1833 and Bao et al., 2008, p. 735). Furthermore, the southwest monsoon influences the area's climate strongly (Cotter, 2011, p. 32).

Jinghong has an annual mean temperature of 23.6° C, and the mean highest and lowest temperatures are 29.5 and 17.7° C (Figure 12). The absolute highest and lowest temperatures are 41.0 and 4.4° C (Zhang et al., 1995, p. 230). Temperatures that are cold enough to cause rubber tree losses happen with certain regularity one out of every eight years since the 1960s (Xu et al., 2006, p. 6). Areas at about 600 m are more exposed to such frosts than lower or higher elevations, and therefore 600 m is not considered to be optimum for rubber growth, but rather elevations below and above that, but not exceeding 800 to 1000 m. Furthermore, the temperature decreases by 0.53° C for every 100 m of elevation (Bao et al., 2008, p. 735).

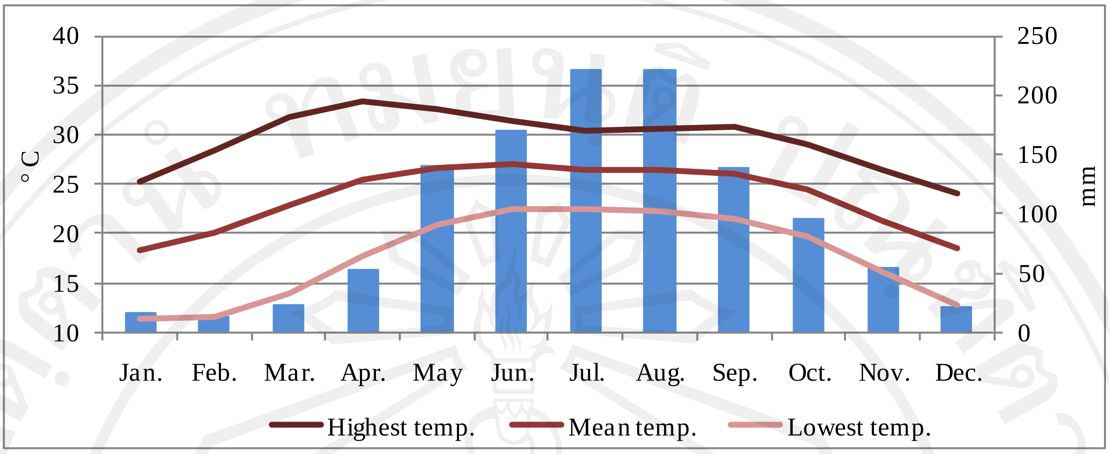

Figure 4 Mean monthly precipitation in mm/month; and mean highest, mean average and mean lowest temperatures in ° C in Jinghong, 1954 to 2007 (Wikipedia: Jinghong)

The area experiences a winter temperature inversion, which occurs in over 80% of the days (i.e. cloudless days) with or without fog between the beginning of December and the end of February. Moreover, there is no frequent temperature inversion during the rest of the year (Jiang, 1981, p. 276-278). The annual amount of hours with sunshine ranges between 1800 and 2300 (Bao et al., 2008, p. 735). The mean monthly atmospheric humidity is from 61.7% to 83.5%, and the mean annual atmospheric humidity is 76.0%. The average annual wind speed is 0.68 m per second. The average reference evapotranspiration is 3.12 mm per day (Tu Tiempo, 1957 - 2012).

2.1.2 Soils

Xishuangbanna has several soil types due to its complex terrain. The soil thickness under rubber plantations is around 70 to 80 cm at low elevations (530 to 650 m), 70 to 75 cm at medium elevations (680 to 800 m), and 50 to 75 cm at high elevations (870 to 1050 m; Jia, 2006, p. 10). Up to date there is no detailed soil map of the NRWNNR. Nevertheless, Langerberger et al. (2010) selected some sites in the reserve, where they described soil profiles. The analysed soils are Latosols* (Oxisols and Ultisols**) at 600 to 900 m, Lateritic Red Earths* (Inceptisols, Oxisols and Ultisols**) between 800 and 1600 m, and Red Mountain Earths* (Alfisols, Inceptisols, Ultisols and Vertisols**) above 1500 and 1600 m. According to the FAO

* Chinese soil classification system
** United States soil classification system

Soil Classification, the three are Ferralsols that have a different content of iron oxides. Furthermore, thick purple soil and limestone are found dispersed in Lateritic Red Earths and in Red Mountain Earths (Bao et al., 2008, p. 735 and Langenberger et al., 2010, p. 11-12).

Latosols have a pH of 4.6 to 5.4, Lateritic Red Earths 5.0 to 5.5, and Red Earths 4.2 to 5.9. Furthermore, red soils often exhibit a deficiency of plant available phosphorous, as they have a high content of aluminium and iron oxides and kaolinite, which strongly adsorb phosphorous. These soils are subject to heavy weathering and leaching; thus, they have a low cation exchange capacity, a low base saturation, and a low water-holding capacity (Langenberger et al., 2010, p. 11-12).

The average daily soil temperature in Jinghong was calculated for a soil depth of 5 cm (Figure 13) using Horton and Corkrey's model, which is dependent on air temperature and on rainfall:

$$T_d = \tilde{\eta} + \tilde{\lambda} L + \tilde{\gamma} \sin\left(\omega(d+\phi)\right) + \kappa \tilde{N}_d + \tau \tilde{M}_d + \nu \tilde{R}_d + \mu \tilde{M}_d \tilde{R}_d \quad , \qquad (1)$$

where L is the latitude of the meteorological station, d is the day of the year, ω is 2π/365, and $\tilde{\eta}, \tilde{\lambda}, \tilde{\gamma}, \phi, \kappa, \tau, \nu, \mu$ (i.e. intercept, latitude, seasonality, phase, air minimum, air maximum, rain and interaction, respectively) and $\tilde{N}_d, \tilde{M}_d, \tilde{R}_d$ are parameters to be estimated (Horton and Corkrey, 2011, p. 307-311).

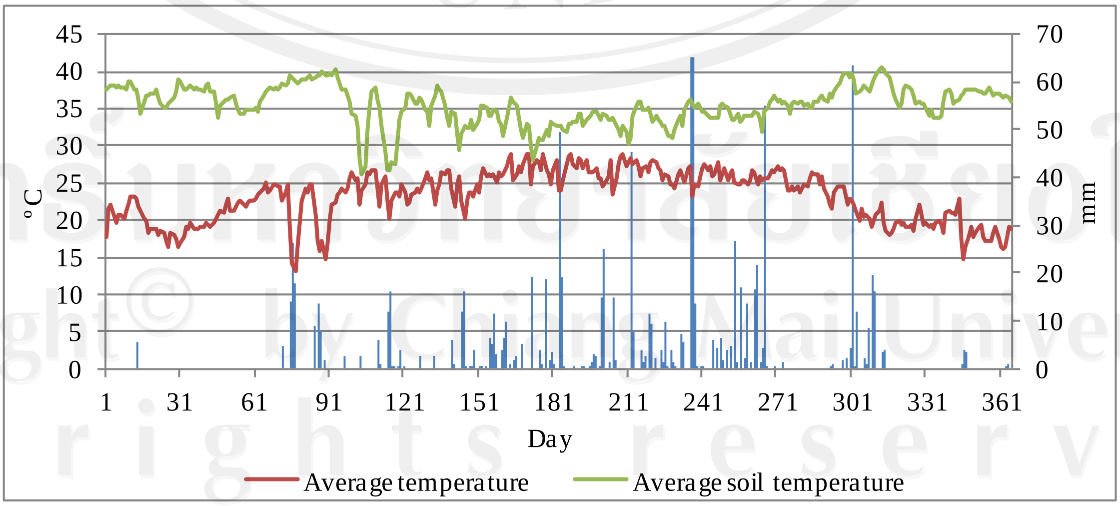

Figure 5 Average daily soil and air temperature in ° C and daily precipitation in mm in Jinghong, 2011

2.1.3 Biological Diversity and Ecosystem Services

Yunnan Province is part of the Indo-Burma hotspot of biological diversity (Conservation International), making it an important area for the conservation of flora and fauna, and as a provider of ecosystems services. As a result, 12.6% of Xishuangbanna's area is covered by nature reserves (Xu et al., 2006, p. 3). Xishuangbanna makes up 0.2% of China's terrestrial area, and is nevertheless home to 16.0% vascular plant (Mo et al., 2011, p. 1833), 21.7% mammal, and 36.2% bird species of the entire country (Xu et al., 2006, p. 2). While Xishuangbanna has 3336 native plant species that belong to 1140 genera and 197 families (Zhu et al., 2006, p. 310), the NRWNNR alone has 1953 vascular plant species from 896 genera and 219 families (LILAC), and 384 vertebrates belonging to 98 families (The Uplands Program, 2010, p. 1). The replacement of primary tropical seasonal rainforests by rubber plantations can lead to a lower species richness and diversity, as forests have about 185 plant species, while rubber plantations only have around 17 plant species (Cotter, 2011, p. 18 and Bao et al., 2008, p. 738).

The NRWNNR's main types of forests are tropical seasonal rainforests that mostly occur below 800 and 900 m, tropical montane rainforests between 700 and 1500 m, and subtropical evergreen broadleaf forests that usually occur above 1000 m (Li et al., 2008, p. 18; WWF, 2009; Mo et al., 2011, p. 1834 and Bao et al., 2008, p. 734). Primary forests tend to have a high amount of biomass per ha, which allows a high biomass carbon sequestration. Nevertheless, not only forests can sequester carbon, but also other land uses, such as rubber and paddy rice. Thus, an ecosystem service that can be offered by the different land uses of the NRWNNR, which is relevant to this study, is carbon storage in biomass. Biomass carbon sequestration is discussed more in depth in Chapter Five.

2.1.4 Land Use

Forests covered 69% of Xishuangbanna's total area in 1976, decreasing to below 50% in 2003, of which tropical seasonal rainforests decreased from 10.9% to 3.6%, while rubber plantations increased from 1.1% to 18.3% and keep increasing (Figure 14; Guardiola Claramonte et al., 2010, p. 5 and Xu et al., 2006, p. 4). Furthermore, over the past years, rubber cultivation has to some extent replaced some agricultural practices, such as orchards, vegetables, tea and maize, as well as primary and secondary forests (Cotter, 2011, p. 2).

The main land uses in the NRWNNR comprise primary and secondary forests (generally subtropical evergreen broadleaf forests) that are mostly located in the core and buffer zones of the reserve, and cover about 70% of the total area; rubber covers 10% of the total area, i.e. 26% and 2% below and above 1000 m, respectively; rice paddies; tea plantations cover 3% of the reserve above 1000 m; settlements; and 22% of the land above 1000 m is used for shifting cultivation (Figure 15; Cotter, 2011, p. 42, 48; Wehner, 2007, p. 3 and Cotter, 2012, personal communication). Rubber plantations are usually located below 1000 m, as frost reduces the rate of survival of rubber seedlings, and latex yield is expected to drop at higher locations (Cotter, 2011, p. 2 and Xu et al., 2006, p. 6).

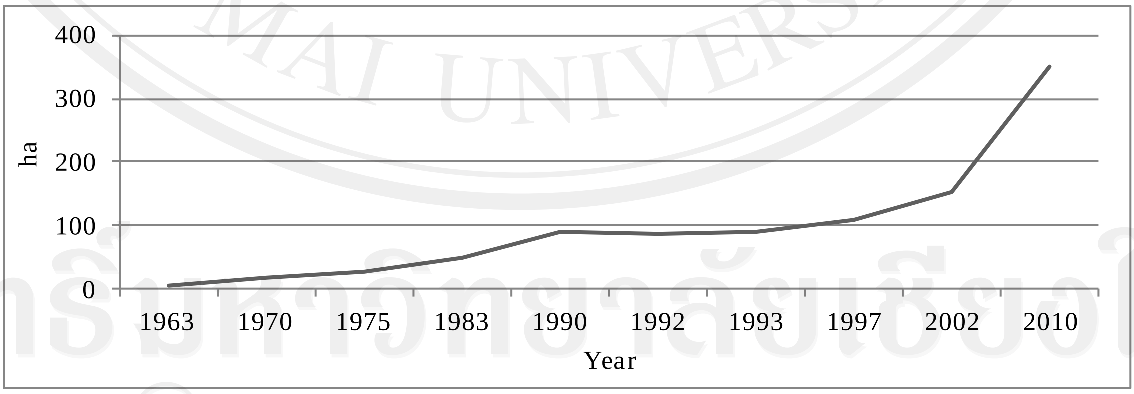

Figure 6 Rubber cover in ha in Xishuangbanna, 1963 to 2010 (Xu et al., 2006, p. 4 and Xu, 2006, p. 256)

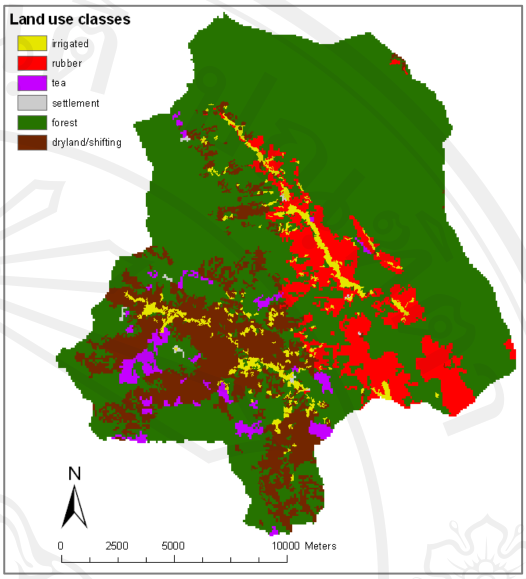

Figure 7 Land uses in the NRWNNR, 2006/07 (Cotter, 2011, p. 42)

Overall in Mainland Montane South East Asia (hereafter MMSEA), including Yunnan Province, a future expansion of rubber in traditional as well as in non-traditional rubber cultivation areas can be expected. Rubber hybrids are being planted in areas above 1000 m (Fox et al., 2011, p. 12-13), and as rubber prices keep increasing, a further expansion of rubber plantations in the NRWNNR is possible. It is expected that by 2050 the land under rubber cultivation and other monoculture crops in the MMSEA will increase by 2 to 4 times, and may to a large extent replace tropical seasonal forests and secondary vegetation. One can additionally expect a threat to subtropical broadleaf forests and secondary swidden-related vegetation (Fox et al., 2011, p. 12-13 and Ziegler et al., 2009, p. 1024), which should be considered when projecting future carbon balance scenarios.

2.1.5 Demography and Economy

Before socialism in Xishuangbanna, the Dai and Hani people lived mostly below 1000 m, were traders and ruling classes; and the Bulang dwelled mostly above 1000 m and practiced slash and burn, tea agroforestry, and livestock farming (Cotter, 2011, p. 3). Nowadays, the lowest village in the NRWNNR is Mangfei at an elevation of 590 m, and the highest one lies at 1800 m (Wehner, 2007, p. 4).

Farmers living above 1000 m rely more on shifting cultivation, while rubber is the major source of income below 1000 m. The livelihoods of the people living in the NRWNNR are mainly based on a mix of rubber, rice, maize, tea, fruits, and horticulture (Wehner, 2007, p. 3, 11). Agriculture in the NRWNNR generates 50% of the income and animal husbandry 20% of it (Schaffert, 2012, p. 12). According to

Wehner (2007, p. 3), most villages try to produce enough rice to cover their own demand. Nevertheless, vegetable production and livestock breeding (pigs and cattle) have decreased and have been partly replaced by rubber, as it offers a higher income. Such situation is creating an increasing dependency on regional markets (Cotter, 2011, p. 4).

Rubber cultivation is an important source of income in Jinghong, where about two thirds of the area under rubber cultivation is managed by the State's rubber enterprises, while one third is managed privately by small-scale farmers. Rubber allows farmers to earn a much higher income than with traditional crops. Compared to swidden farming, perennial rubber plantations have led to an income increase of up to €3,581[6] per ha (Cotter, 2011, p. 3-4). Rubber farmers earn around €3,581 per ha the first five years of tapping, and €8,950[7] per ha between the 5th and 12th year of tapping. Appropriate field management can lead to earnings of up to €5,370[8] per ha between the 13th and 40th year of tapping[9] (Tang et al., 2009, p. 34).

Beyond the possibility of an important additional income generation from rubber cultivation, rubber in the NRWNNR does not grow under what are considered suitable climatic characteristics for rubber cultivation. This can result in a lower biomass development that in turn leads to lower latex yields, as well as to a lower carbon sequestration capacity compared to more suitable environments. Therefore, the following chapter gives a description of the rubber plant or *Hevea brasiliensis*.

[6] 1 EUR = 8.38 CNY: 03.04.2012
[7] 1 EUR = 8.38 CNY: 03.04.2012
[8] 1 EUR = 8.38 CNY: 03.04.2012
[9] Based on rubber prices of 2008.

2.2 *Hevea brasiliensis*

The plant *Hevea brasiliensis* (Willd. ex A.L. Juss.) Muell. Arg. (Figure 16) is commonly known as natural rubber (hereafter rubber), and belongs to the family Euphorbiaceae (Jansen et al., 1998, p. 226 and Judd et al., 2008, p. 271). Rubber is mainly planted in tropical regions (Priyadarshan, 2011, p. 142-147), mostly for latex exploitation (Cotter et al., 2009, p. 11), and is the world's major source of natural rubber (Judd et al., 2008, p. 271 and Nair, 2010, p. 237).

Figure 8 Rubber plantation in the NRWNNR (Blagodatskiy, 2012)

Rubber is native to permanently humid and wet tropical parts of the Amazon Basin, Mato Grosso, Upper Orinoco, and the Guianas, which rarely have marked seasonal changes (Lim, 2012, p. 477; Smartt et al., 1995, p. 124-125 and Nair, 2010, p. 238). These areas lie between latitudes 10° N and 10° S, and at an elevation of maximum 600 m (Guardiola Claramonte et al., 2010, p. 9). The world's main areas under rubber cultivation lie between latitudes 15° N and 10° S (Yeang, 2007, p. 284 and Orwa et al., 2009, p. 2). In 2010, 91% of the world's rubber plantations were located in Southeast Asia at elevations hardly above 100 m, followed by West Africa, and finally tropical America (Lu et al., 2010, p. 4 and Rubber Asia).

Rubber is a deciduous perennial tree that sheds its leaves (wintering) in the dry season (Priyadarshan, 2011, p. 25 and Nair, 2010, p. 267). Its economically useful life is between 30 and 35 years (Smartt et al., 1995, p. 124 and Rao et al., 1998), and then trees need to be replanted (Orwa et al., 2009, p. 4). Rubber is an outbreeding tree species (Yeang, 2007, p. 284) that can grow up to 30 m high (Nair, 2010, p. 244). It has a straight trunk of usually over 50 cm in girth, which is covered by a light gray bark. The wood density of rubber is 0.6 g per cm^3. The branches produce an open crown with many leaves (Nair, 2010, p. 266-267; Orwa et al., 2009, p. 1 and Abd Karim, 2006, p. 4).

Rubber trees of 3 and 7 to 8 years can have 1.5 and 2.4 m long taproots, and 6.0 to 9.0 m and over 9.0 m long laterals, respectively (Priyadarshan, 2011, p. 26 and Orwa et al., 2009, p. 1). The flowers are greenish in colour (Lock, 1913, p. 35). A plant alone has female and male flowers that are produced in different sections of the plant; pollination is mostly by allogamy by insects, such as, e.g., midges, thrips, and honeybees; and autogamy can happen in several degrees (Smartt et al., 1995, p. 125; Orwa et al., 2009, p. 1 and Cotter, 2011, p. 16). Hermaphroditic flowers are rare, but were described in some rubber clones (Cuco and Bandel, 1994, p. 413 and Cuco and Bandel, 1998).

The fruit is light brown when ripe, and between 3 and 7 cm in diameter (Figure 17; Plantwise and Tropical Biology Association: *Hevea brasiliensis*). It mostly has three carpels (rarely 4 or 5), each usually contains one ovoid spotted seed of around 2.0 to 3.5 cm by 1.5 to 3.0 cm that weighs between 3 and 6 g (Figure 18; Priyadarshan, 2011, p. 22, 24; Orwa et al., 2009, p. 1 and Nair, 2010, p. 244-245). Propagation can be vegetatively or through seeds (World Agroforestry Centre). The genus Hevea has ten species, and experimental crosses among them did not show genetic barriers (Smartt et al., 1995, p. 125 and Priyadarshan, 2011, p. 74). However, some clones are not self-compatible (Orwa et al., 2009, p. 1).

Figure 9 Rubber fruits (Steven Alexander, 2011)

Figure 10 Rubber seeds (Wikipedia: *Hevea brasiliensis*)

Leaf shedding in Xishuangbanna begins the first days of January, and lasts 2.5 to 4 weeks, leaving trees without leaves for 11 to 19 days. The growth of new leaves begins during the first half of February. Flowering occurs in the second half of March, and ends during the first half of April (Table 1; Jia, 2006, p. 16).

Table 1 Phenological stages of mature rubber plantations in Xishuangbanna*

Stage	Sub-stage	Low elevation (day.month)	Medium elevation (day.month)	High elevation (day.month)
Budding	Growth	25.01	21.01	24.01
	Unfold	31.01	26.01	29.01
Leaf growth	Beginning	19.02	10.02	8.02
	Total	23.02	16.02	13.02
Flowering	Flower in bud	9.03	28.02	-
	Beginning	24.03	15.03	-
	Complete	29.03	22.03	-
	End	15.04	11.04	-
Fruit	Ripe	11.08	6.08	-
	Begin falling	25.08	22.08	-
	Finish falling	23.09	17.09	-
Leaf discolour	Beginning	5.01	1.01	28.12
	Complete	26.01	14.01	10.01
Leaf shedding	Beginning	9.01	3.01	1.01
	End	7.02	25.01	19.01

(Jia, 2006, p. 16)

* No climatic phenomenon occurred during the observation time

After flower fertilization, fruits need 5 to 6 months to ripen (Smartt et al., 1995, p. 126). In the northern hemisphere, minor flowering can occur in several regions during August and September. Most likely flowering occurs as a response to an increase in solar irradiation on the surface and can be emphasized by the switch from the dry to the rainy season (Smartt et al. 1995, p. 126; Rao et al. 1998, p. 235; Priyadarshan, 2011, p. 18 and Yeang, 2007, p. 284). Rubber does usually not produce flowers and fruits at 1000 m and above. Furthermore, most of the rubber tree's growth takes place during the rainy season (Lim, 2012, p. 477 and Jia, 2006, p. 4, 16).

2.2.1 Cultivation

The following part gives an insight into the main requirements for rubber to achieve high biomass and latex yields. The main contributors to latex yield variability in different climatic areas are considered to be rainfall, atmospheric humidity, temperature, sunlight, and wind speed. Furthermore, management and soil also influence yield (Rao et al., 1998, p. 236 and Liu et al., 2010, p. 381). These requirements are derived from the rubber's natural habitat, and studies regarding rubber plantations in different areas worldwide.

The germination of rubber seeds starts around 3 to 5 days after sowing (Priyadarshan, 2011, p. 24), and the most appropriate time for seedling transplantation is during the monsoon. The suggested size of planting pits is 75 x 75 x 75 cm, or 90 x 90 x 90 cm (Purdue University). Rubber starts to yield latex at an age of 8 years in Xishuangbanna (Tang et al., 2009, p. 34), at 4 to 7 years in more suitable cultivation areas. Rainfed rubber in some areas in India may need over 10 years to yield latex (Rao et el., 1998, p. 235; Priyadarshan, 2011, p. 18 and Vijayakumar et al., 1998, p. 245). Furthermore, latex yield has a positive correlation with girth, which must be at least 45 cm to be tappable (Lu et al., 2010, p. 6).

2.2.2 Temperature, Sunlight and Wind

The habitat of rubber is characterized by minor variations in air temperature between 25 and 28° C (Guardiola Claramonte et al., 2010, p. 9 and Lim, 2012, p. 477). Rubber performs best at these temperatures, but not lower than 20° C and not above 34° C (Orwa et al., 2009, p. 2 and Cotter et al., 2009, p. 12). Optimum photosynthesis takes place between 27 and 33° C. Rubber is susceptible to high temperatures, such that at 35° C stomata close, decreasing photosynthesis and increasing respiration. Furthermore, the maximum temperature to which rubber is exposed throughout 1, 7 and 30 days before tapping is responsible for around 32%, 42% and 64%, respectively, of the daily variability in yield (Rao et al., 1998, p. 235-236).

Lower temperatures generally allow an increase in latex yield (Rao et al., 1998, p. 242-243). Furthermore, rubber seeds are able to germinate at even 10° C, while the boundary temperature for chilling injury of young trees is between 15 and 16° C (Black et al., 2006, p. 82). However, high yielding frost-resistant rubber trees that are especially adapted to Yunnan's climatic characteristics have been developed; among them are PR107, GT1, PB86, and RRIM clones (Lu et al., 2010, p. 5).

Rubber needs about 6 hours of sunshine per day, i.e. 2190 sunshine hours per year, but not less than 3 nor over 7 hours per day (Cotter et al., 2009, p. 12). Furthermore, average wind speeds of over 2 m per second per year are negatively correlated with latex yield, and can also damage trunks and branches. However, there are clones with a higher resistance to wind (Smartt et al., 1995, p. 126; Lu et al., 2010, p. 4 and Orwa et al., 2009, p. 2). Overall, too high temperatures, extended daylight duration, vapour pressure deficit, and high evaporation have a significant negative correlation with latex yield when considering a time period from 7 up to 180 days (Rao et al., 1998, p. 241-242).

2.2.3 Water and Irrigation

Precipitation in the rubber's habitat ranges between 1500 and 2000 mm per year (Guardiola Claramonte et al., 2010, p. 9). Rubber performs best with 2000 to 2500 mm rainfall per year, but below 1500 mm and over 4000 mm should be avoided. Nevertheless, there are some rubber clones that can be grown with 1500 mm. Rubber does not tolerate drought well and requires a minimum of 100 rainy days in a year, a rainy season of 11 to 12 months, and not more than 2 to 3 consecutive months of drought for optimum performance (Lim, 2012, p. 477; Orwa et al., 2009, p. 2 and Cotter et al., 2009, p. 12). A monthly precipitation of 125 mm and a potential evapotranspiration of 4 mm per day, which are uniformly distributed throughout the year, are needed to keep optimum gaseous exchange of rubber trees (Vijayakumar et al., 1998, p. 246). Furthermore, there is a significant positive correlation between yield and cumulative rainfall beyond a one month period (Rao et al., 1998, p. 235, 241).

Heavy precipitation for a long time period may reduce yield, due to the lower photosynthesis rate when simultaneously sunlight duration is short and rainfall is high (Rao et al., 1998, p. 243). Ideally, rubber should not be water logged, only up to maximum 3 days (Cotter et al., 2009, p. 12). It grows best with an atmospheric humidity of about 80% (Lim, 2012, p. 477). Furthermore, it is adapted to minor rainfall changes, making soil moisture especially important as it supplies the plant with moisture during a part of the dry season. Rubber transpires 4 to 6 mm water vapour per day when soil moisture is adequate, and 2 to 4 mm per day when it is not. Nonetheless, the tree itself is not seriously affected when exposed to a short dry period, as long as there is enough soil moisture to support nutrient uptake and evapotranspiration, among others (Rao et al., 1998, p. 236, 243-244).

Soil moisture stress changes plant water relations, leading to the reduction of the leaf area and consequently of the photosynthesis rate, which negatively affect yield and biomass development (Rao et al., 1998, p. 243; Nair, 2010, p. 261 and Vijayakumar et al., 1998, p. 258). Moisture stress also affects yield, due to the high moisture content of latex. Thus, the intensity and the time period of moisture stress can partly explain the difference among annual yields in different regions. Furthermore, moisture stress and rain may partially contribute to determine the 5 to 6% day-to-day variability in yield at the same location. Moreover, high soil moisture content can result in latex dilution (Nair, 2010, p. 248 and Rao et al., 1998, p. 243).

Rubber is mostly irrigated in regions with distinct dry periods, as they can put plants under severe water stress (Nair, 2010, p. 260). Such region is North Konkan in India, where two different irrigation treatments (basin and drip irrigation) were applied to rubber trees from 1990 until 1994. Both treatments showed increases in girth, biomass, and percentage of tappable trees compared to the control (Table 2). This shows that rubber requires irrigation for better growth during long periods of drought. Furthermore, enough irrigation showed to reduce and remove foliar injury, which leads to a higher rate of photosynthesis (Vijayakumar et al., 1998, p. 245, 250, 254).

Table 2 Effect of different irrigation treatments on girth increment, biomass production and tappable trees (January 1994) in rubber in North Konkan, India

Treatment	Girth in cm	Biomass in kg per tree	Tappable trees in %
Control	34.3	49	0.0
0.50 basin	46.6	113	12.0
0.75 basin	49.5	134	50.0
1.00 basin	49.9	137	53.6
0.25 drip	41.6	83	3.2
0.50 drip	45.0	103	1.6

0.75 drip	46.3	111	20.0
CD (0.01)	5.3	30	2.36

(Vijayakumar et al., 1998, p. 250).

2.2.4 Soils and Fertilization

Rubber mostly occurs on deep, well-drained soils that may become slightly seasonally flooded, have a pH below 6.5, and no underlying sheet rocks (Smartt et al, 1995, p. 124 and Nair, 2010, p. 261). It grows well on deep, well-drained, weathered clayiy-loamy to loamy soils with high fertility; clayey soils (e.g., Oxisols and Ultisols) with low fertility; and alluvial, sedimentary, laterite, lateritic, and non-lateritic red soils (Lim, 2012, p. 477). Rubber can tolerate a pH between 3.5 and 8.0, but performs best with a pH of 4.0 to 5.0. The most suitable soil carbon content is above 2.5% and not lower than 0.5%. Soil fertility should ideally be very high, and not less than low. Furthermore, rubber can be damaged by lime, and does not thrive well on soils that are shallow, have a deficient drainage or consist of peat (Cotter et al., 2009, p. 12 and Orwa et al., 2009, p. 2).

The roots of rubber support soil binding, as the tree takes up most nutrients and water from the soil surface (Nair, 2010, p. 267) during the rainy season and from deeper soil layers during the dry season (Rao et al., 1998, p. 236). Furthermore, rubber grows best with a groundcover and erosion protection (Orwa et al., 2009, p. 2). Therefore, nitrogen fixing crops have been used for a long time in rubber plantations to reduce erosion on sloping land and to increase N availability (Priyadarshan, 2011, p. 126-127). Such crops have shown to improve soil fertility and increase soil organic matter, which can additionally improve soil aggregate stability, water infiltration, and water holding capacity (Nair, 2010, p. 267).

As rubber has a need for high soil fertility, it is recommended to regularly apply nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) fertilizers during its entire productive life. Additionally, the unproductive stage of the tree can be shortened by appropriate fertilizer application during the immature phase, since it accelerates growth. In the mature phase, N, P, K and Mg influence biomass development and yield positively, and NPK-fertilizer[10] input leads to a considerable increase in yield (Nair, 2010, p. 261, 267).

Rubber plantations in the NRWNNR receive different types and amounts of fertilizers according to their ages. To stimulate growth, urea is applied two times a year after rubber is planted, from the third year until maturity compound fertilizer is applied once a year. Mature plantations are fertilized twice a year with manure, artificial fertilizer, and urea (Table 3; Tang et al., 2009, p. 33).

Table 3 Fertilization of rubber plantations in the NRWNNR

Tree age in years	Fertilizer	Amount in kg per ha	Application
1 to 3	Urea	60	April and November
3 to 8	Artificial	215	November
Over 8	Artificial	600	April and November
Over 8	Urea	450	April and November
Over 8	Manure	7500	April and November

(Tang et al., 2009, p. 33)

[10] NPK fertilizer has the main function to supply a plant with nitrogen, phosphorous and potassium.

2.2.5 Diseases and Pests

Rubber is susceptible to a broad variety of pests, diseases and fungi, depending on its specific location, climate, management, and the cultivated clone. The main and most harmful disease of rubber in tropical America is South American leaf blight (SALB), caused by *Microcyclus ulei*, but has not reached Asia yet. Other important diseases affecting rubber are abnormal leaf fall (ALF), caused by Phytophthora spp.; and secondary leaf fall (SLF), caused by *Colletotrichum gloeosporioides*, *Corynespora cassicola* (leaf spot disease), *and Oidium heveae* (powdery mildew). *Corticium salmonicolor* causes pink disease, which leads to drying of major stems and branches of 3 to 7 year old trees (Priyadarshan, 2011, p. 153, 158-160 and Nair, 2010, p. 261-262).

Further predominant fungi on rubber cause leaf spot (*Botryodiplodia elactica*, *Botryodiplodia theobromae*, *Colletotrichum heveae*), brown root rot (*Fomes lamaensis*), white spongy rot (*Polystichus personii*), red rot (*Sphaerostilbe repens*), charcoal rot (*Ustulina maxima*), die back (*Gloeosporium heveae*), and rim bright (*Sphaerella heveae*, *Polystichus occidentalis*). Rubber is also susceptible to nematodes, like *Helicotylenchus cavenessi*. Trees at any age can be damaged by white ants, and several kinds of animals cause injuries to the trunks. Pests may include snails on young trees, thrips, mites, termites, and cockchafers. Phytophthora spp. can cause black stripe that negatively affects tapping panels (Nair, 2010, p. 262 and Purdue University).

In the NRWNNR, rubber plantations can be susceptible to white powder sickness and to scale insects, and require the application of pesticides (Table 4; Tang et al., 2009, p. 34). Overall, young rubber plants are exposed to more competition with weeds than in their mature stage. Weeding is considered to be more efficient by combining manual weeding, synthetic herbicide application and establishing cover crops (Nair, 2010, p. 259-260).

Table 4 Application of pesticides in rubber plantations in the NRWNNR

Disease or pest	Symptom	Pesticide	Amount in kg/ha	Application
White powder sickness	White spots on the leaves	Triadimefon or Sulphur powder	37.5	Late February or early March
Scale insects	Leaves become black	Rogor	"some"	Straightaway

(Tang et al., 2009, p. 34)

2.2.6 Tree Spacing and Intercropping

Depending on the planting density, the canopy of rubber trees usually closes in the fourth to fifth year, and as a result, trees start to compete more. Yet, the leaf area index (LAI) of mature rubber trees is alike with 500 to 800 trees per ha (Nair, 2010, p. 267 and Priyadarshan, 2011, p. 28, 130). In Xishuangbanna, the LAI remains quite stable with 3.5, 3.0 and 2.5 at low, medium and high elevations, respectively, and is significantly different among the different elevations (Jia, 2006, p. 4).

Most experiments on planting density showed that the amount of timber and latex produced by a single rubber tree decrease with increasing planting densities. Nonetheless, timber and latex volume per ha increase. However, when the density is too high, the yield per ha may decrease, and therefore optimum densities lie between 500 and 700 trees per ha (Priyadarshan, 2011, p. 27-28). Rubber in Xishuangbanna is mostly planted in rows of trees of the same age (Xu et al., 2006, p. 4), and tree densities per ha are 450 to 525 at low elevations, 450 to 525 at medium elevations, and 450 to 570 at high elevations (Jia, 2006, p. 10).

Lower rubber tree densities are recommended for intercropping (Purdue University). Groundcover as well as intercrops are becoming more usual, and require managing intercrops properly to reduce competition with rubber (Nair, 2010, p. 267). Excluding grasses, most crops that are intercropped with rubber do not affect rubber development negatively and in many cases lead to a better growth of rubber (Priyadarshan, 2011, p. 131).

2.2.7 Latex Properties and Collection

Figure 11 Latex tapping from a rubber tree in the NRWNNR (Blagodatskiy, 2012)

Latex is a colloidal suspension (Priyadarshan, 2011, p. 46) that is composed of 60 to 70% water, 25 to 40% rubber, 1.5 to 2.0% resins, 1.5 to 2.0% proteins, and 0.5 to 1.0% minerals (Nair, 2010, p. 250 and Universität Marburg). Dry matter content is between 20 and 25%, of which about 90% is rubber (Priyadarshan, 2011, p. 47). Latex is obtained by cutting the rubber tree's latex vessels that are in the inner bark, so that latex flows and can be collected (Figure 19; Purdue University and Cotter et al., 2009, p. 11). Latex yields are usually highest at a tree age between 15 and 20 years. Trees originating from unselected seedlings can yield about 600 kg per ha per year, while some clones can surpass 2000 kg (Janssens et al., 2003, p. 94). The yield of dry rubber is between 3.0 to 4.5 kg per tree per year, and the potential yield is 8.5 kg per tree per year (Cotter, 2011, p. 16).

One of the tapping systems used in Xishuangbanna on RRIM600 rubber clones is S/2 (one half spiral cut) d2 (alternate day tapping). Tapping in the NRWNNR usually takes place every other day (d2), i.e. that every tree is cut about 100 times per season. The yield in Xishuangbanna varies throughout the tapping period, which begins at the end March and finishes in November (Figure 20; Jia, 2006, p. 9; Rubber Board – India and Wehner, 2007, p. 11).

Ethephon (2-chloro-ethyl-phosphonic acid) is used in rubber cultivation to increase yield through the stimulation of ethylene (C_2H_4) production, which delays latex and vessel plugging. The stimulator can increase the yield by 20 up to 100%, which is sustained for a period of minimum three months. Ethephon application usually leads to a decrease in dry rubber content of 2 to 7%, but has no impact on rubber characteristics (Nair, 2010, p. 248-249).

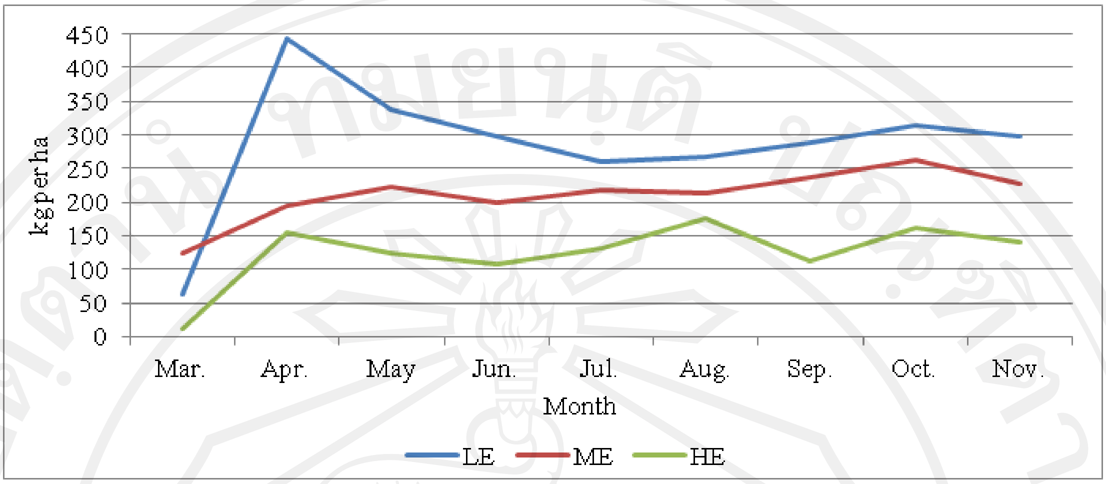

Figure 12 Dry latex yield at low, medium and high elevations during the tapping period in Xishuangbanna (Jia, 2006, p. 26)

2.2.8 Limiting Factors

Rubber has the ability to be sufficiently productive to generate an important amount of additional income in some locations that are not considered to be optimal for rubber cultivation, as the NRWNNR (Guardiola Claramonte, 2010, p. 9 and Cotter, 2011, p. 3-4). Nevertheless, some factors can influence the biomass development and yield of rubber negatively. Extremely high temperatures can lead to yield drops (Orwa et al., 2009, p. 2 and Rao et al., 1998, p. 236). On the other hand, low temperatures and high wind speeds can reduce yield, and cause injuries and tree loss (Black et al., 2006, p. 82; Smartt et al., 1995, p. 126 and Lu et al., 2010). Extended daylight duration and vapour pressure deficit also influence yield negatively. Furthermore, the yield tends to be lower throughout the dry season, and moisture stress can reduce yield and biomass growth drastically (Rao et al., 1998 and Vijayakumar et al., 1998, p. 258).

A pH above 8.0, extended waterlogging, deficient drainage and lime can have large negative impacts on biomass growth and yield (Tropical Biology Association: *Hevea brasiliensis* and Orwa et al., 2009, p. 2). Moreover, rubber trees planted above 400 to 500 m.a.s.l. are usually shorter in height, grow more slowly, and have a lower yield and biomass development (Orwa et al., 2009, p. 2). If seeds are not managed after fruit harvest, seed storage is not successful for more than 10 to 15 days, period in which they should be sown (Priyadarshan, 2011, p. 24). Furthermore, rubber can be

2.2.9 Current Distribution of Rubber Plantations

Rubber is cultivated in countries where it is native to, i.e. in some regions of Bolivia, Brazil, Colombia, Peru, and Venezuela. Plantations where rubber is exotic comprise Australia, Brunei, Cambodia, China, Ethiopia, Fiji, India, Indonesia, Laos, Liberia, Malaysia, Micronesia, Myanmar, Nigeria, Papua New Guinea, Philippines, Samoa, Singapore, Sri Lanka, Tanzania, Thailand, Uganda, and Vietnam (Orwa et al., 2009, p. 2; Nair, 2010, p. 242 and Tropical Biology Association: *Hevea brasiliensis*).

In 2010, rubber covered an area of 11.5 million ha worldwide, resulting in the production of 10.3 million Mg of rubber (Rubber Asia). It is expected that by 2018 14.9 million Mg will be produced (Information Center for Natural Rubber, p. 3-4). The world's largest rubber producing countries include Indonesia - 3,329,000 ha, Thailand - 1,968,000 ha, Malaysia - 1,315,000 ha, China - 618,000 ha, and India - 573,000 ha; other important rubber producers are Vietnam in Asia, Liberia and Ivory Coast in Africa, and Brazil and Guatemala in Latin America (Smartt et al., 1995, p. 124; Nair, 2010, p. 242 and Cotter et al., 2009, p. 12).

Rubber is also planted in latitudes that are considered to be marginal for rubber due to diverse climatic conditions, and reach up to 29° N in India and China, and up to 23° S in Brazil (Rao et al., 1998, p. 235-236 and Yeang, 2007, p. 284). Rubber plantations in such latitudes and at ever higher elevations are increasing, regardless the decrease of productivity under the prevalent climatic conditions (Guardiola Claramonte, 2010, p. 9). Rubber cultivation in China has expanded fast (Nair, 2010, p. 242) and covers parts of the provinces of Hainan, Guangdong, Fujian, Yunnan and Guangxi that are located in latitudes 18 to 24° N (Priyadarshan, 2011, p. 144).

Rubber is mainly exploited for its latex (Cotter et al., 2009, p. 11) and currently covers about 40% of the world's rubber demand (FAO, 2008). Major exploited by-products include rubberwood, honey, and seeds that are processed to oil and seedcake

(Nair, 2010, p. 265-266). Rubber is used for the production of around 50,000 products that can be found in all kinds of vehicles, airplanes, ships, factories, hoses, clothing, pharmaceuticals; it is used for sealing, insulation, conveying, and shock damping, among others (Cotter et al., 2009, p. 11 and Nair, 2010, p. 237-238).

Optimal requirements for rubber cultivation cannot be found in the NRWNNR regarding rainfall amount and distribution, elevation, and average annual temperatures at medium (22.0° C) and high (20.4° C) elevations. Nevertheless, rubber flourishes there and offers an important additional income opportunity to rubber farmers. In order to be able to make an estimation of the importance of using rubber as a means for carbon sequestration, it is necessary to estimate the amount of carbon it can accumulate compared to other important land uses in the NRWNNR, which are paddy rice, maize, orchards/tea, grasslands, and primary and secondary forests.