Measuring and modelling carbon stocks in rubber (*Hevea brasiliensis*) dominated landscapes in Subtropical China

Xueqing Yang

FACULTY OF AGRICULTURAL SCIENCES

Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute)

University of Hohenheim

Field: Plant Production in the Tropics and Subtropics

Prof. Dr. Georg Cadisch

UNIVERSITÄT HOHENHEIM

Measuring and modelling carbon stocks in rubber (*Hevea brasiliensis*) dominated landscapes in Subtropical China

Dissertation
Submitted in fulfilment of the requirement for the degree
"Doktor der Agrarwissenschaften"
(Dr.sc.agr./Ph.D. in Agricultural Sciences)

to the
Faculty of Agricultural Sciences

Presented by:
Xueqing Yang

Born in:
Yunnan, China

Submitted in: July 2018, Stuttgart

This thesis was accepted as doctoral dissertation in fulfilment of the requirements for the degree "Doktor der Agrarwissenschaften" (Dr.sc. Agr./ PhD in Agricultural Sciences) by the Faculty of Agricultural Sciences at University of Hohenheim on Augest 7, 2018

Date of oral examination: Janurary 30, 2019

Examination Committee

Supervisor and Reviewer	Prof. Dr. Georg Cadisch
Co-Reviewer	Prof. Dr. Jianchu Xu
Additional Examiner	Prof. Dr. Folkard Asch

Acknowledgement

Undertaking this PhD has been a life-changing experience for me, and I would like to extend thanks to many people, who are so generously contributed to the work presented in this thesis.

First of all, I would like to thank Prof. Dr. Georg Cadisch for accepting me as his student. “Georg” is my primary inspiration resource for getting my science questions raised and answered, accompanying with continuous critical thinking. Without his guidance and constant feedback this PhD would not have been achievable. I would like to further express my gratitude to my co-supervisor Dr. Sergey Blagodatskiy, for providing me with insightful discussions and suggestions. We always acting as strong alliance to solve the research problems, and represent nicely to our potential audience. Many thanks also go to Prof. Dr. Jianchu Xu, who has given me the freedom to pursue various interesting aspects of research during my master study. His way of creative thinking and resourceful advice, is great motivation to push me keep learning and empower myself for future career. Here, I am grateful to Dr. Carsten Marohn, who regularly organized us with “modelling group” and I can always get rapid feedback through provoking discussions and professional knowledge. I am also highly indebted to Prof. Dr. Jianchu Xu and Prof. Dr. Folkard Asch for kindly accepting to act as co-examiners of my PhD thesis.

I greatly appreciated the funding received towards my PhD from the German-Chinese joint project SURUMER (Sustainable Rubber Cultivation in the Mekong Region), funded by the German Federal Ministry of Education and Research (BMBF) and by the German BMZ/GIZ funded Green Rubber project. Thanks to our project important partners Zhongqing Li and Feng Liu for providing supportive facility for field site survey and essential data collection within Naban Watershed National Nature Reserve (NWNNR). Great thanks to Lijuan Duan and all project colleagues, we sharing our unforgettable memory in every little moment during whole project, which made foundation for our life-long friendship. Besides this, thanks to my efficient and hard-working field assistants Yuan He, Guanghui Liu, Dian Chen, without whom the essential dataset could not be collected.

I would like to acknowledge the contributions of my colleagues/friends from ICRAF East & Central Asia office, as well as from Kunming Institute of Botany, CAS. Thank you to Mingming Wang, Mei Yang, Zhengli Li, Xiaonan Shi, Lijuan Liu, Lu Li, Yunshan Wang for the supportive and professional help in project administrative things. Prof. Dr. Robert J. Zomer and Mingcheng Wang has shared me with downscaled climate change scenarios for my modelling study; Prof. Dr. Rhett D

Harrison, Prof. Dr. Jianwei Tang, Dr. Sailesh Ranjitkar, Dr. Haiying Yu, Dr. Zhuangfang Yi, Dr. Deli Zhai, Dr. Yixin, Zhu, Dr. Shi Min, Dr. Marc Cotter, Dr. Arisoa Rajaona, Dr. James Hammond, Dr. Philip Beckschäfer and Dr. Gerhard Langenberger has joined many instructive discussion in serval aspects of my PhD case studies. I am appreciate encouragement and academic advice from Prof. Dr. Xuefei Yang and Prof. Dr. Jun He. Thanks to Prof. Dr. Meine van Noordwijk，who provided instructive comments for improvement of my manuscripts. I owe gratitude to Dr. Mart-Jan Schelhaas, who offered me with great hospitality and robust scientific support during my stay at the Team Vegetation, Forest and Landscape Ecology of Wageningen Environmental Research (WENR). I got to know other modelling researchers such like Prof. Dr. Gert-Jan Nabuurs and Dr. Richard Sikkema, which was a wonderful scientific visiting experience.

I would like to convey my heartfelt gratitude to the members of Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute, 490e). Thanks Gaby Kircher for everything, who actively prompts whole institute progress and makes it home-feeling. Special thanks to PD. Dr. Frank Rasche, who shows constant faith in scientific research, and kindly provides detailed guidance to students from lab-experiment to project-funding application. I wish to thank Dr. Thomas Hilger, who generously provided SUNSCAN from temperate Germany to tropical China for my field LAI measurement. Thank you also go to Catherine Meyer, who squeezed her valuable examination-preparation time to translate my dissertation summary into German version. I cannot neglect to mention the PhD students (some are departure now): Dr. Melvin Lippe, Dr. Khalid Hussain, Dr. Esther Muema, Dr. Mary Musyoki, Dr. Johanna I.F. Slates, Dr. Juan Carlos Laslo-Bayas, Christian Brandt, Hongxi Liu, Thanh Thi Nguyen, Yvonne Nkwain, Tongkoom Krittiya, Reza Golbon, Hannes Karwat, Irene Chukwumah, Isaac Balume, Moritz Laub, Ruj Kasetsuwan, Kevin Thellmann and many others, sincerely thanks for your support, encouragement and friendship.

My deepest gratitude goes to my family for their unflagging love and unconditional support throughout my life; this dissertation is simply impossible without them. I am indebted for their love, their sacrifice, their understanding and their accompanying during my ups and downs. This list of acknowledgements can only capture a small fraction of the people who supported my work. I send my deepest thanks to all. Your contributions to this dissertation were vital, but the inevitable mistakes in it are entirely my own.

Xueqing Yang

Table of Contents

List of tables

List of figures

List of abbreviations

AGB: aboveground biomass

AIC: Akaike information criterion

BGB: below ground biomass

BMBF: German Federal Ministry of Education and Research

C_{ta} : time-averaged carbon stock

CART: classification and regression tree

CF: correction factor

CMIP5: Coupled Model Intercomparison Project- Phase 5

COS: conservation oriented scenarios

CS: coefficient of sensitivity

CSA: climate-smart agriculture

CSL: climate-smart landscape

DBH: diameter at breast height

DEM: Digital Elevation Model

DGVMs: Dynamic Global Vegetation Models

EOS: economic oriented scenario

ESM: Earth System Models

FBA: functional branches analysis

FRAs: Global Forest Resources Assessments

GIS: Geographic Information System

IGBP: International Geosphere –Biosphere Programme

IPCC: Intergovernmental Panel on Climate Change

LAI: leaf area index

LDD: local drainage direction

LILAC: Living Landscapes China Project

LUCIA: Land Use Change Impact Assessment model

LULC: land-use/land-cover

m a.s.l: metres above sea level

MMSEA: Montane Mainland Southeast Asia

NPP: Net Primary Production

NPV: Net Present Value

NRWNNR: Naban River Watershed National Nature Reserve

NTFP: Non Timber Forest Products

PAR: photosynthetically active radiation

PES: Payment for Ecosystem Service

RaCSA: Rapid Carbon Stock Appraisal

RCPs: Representative Concentration Pathways

REDD: reducing emissions from deforestation and forest degradation

REDD+: reducing emissions from deforestation and forest degradation, plus the sustainable management of forests and enhancement of forest carbon stocks

RMSE: root mean square error

RS: Remote Sensing

R/S: root-to-shoot ratio

SEA: South East Asia

SLA: specific leaf area

SLCP: Sloping Land Conversion Program

SOC: soil organic carbon

SURUMER: Sustainable Rubber Cultivation in the Mekong Region Project

TB: total biomass

UNESCO: United Nations Educational, Scientific and Cultural Organization

Chapter 1

General Introduction

Chapter 1 General introduction

The study presented in this thesis was supported by the German-Chinese joint project SURUMER (Sustainable Rubber Cultivation in the Mekong Region), funded by the German Federal Ministry of Education and Research (BMBF) under Grant number FKZ 01LL0919 and by the German BMZ/GIZ funded Green Rubber project with project number #13.1432.7-001.00. The objective of the SURUMER is to develop an integrative, applicable, and stakeholder-validated concept for sustainable rubber cultivation in rubber cultivated regions across the Great Mekong region. The whole program included 9 subprojects which involved an ecosystem service analysis (carbon dynamic, water balance and management, pollinator services, agro-ecological diversification, human-wildlife conflicts) and ecosystem service benefit evaluation (welfare economic valuation, microeconomic analysis) and knowledge transferring from scientific research to local and regional management. The work of the presented cumulative PhD thesis was conducted within the subproject SP1 which aimed to assess the impact of intensified rubber cultivation on spatial and temporal carbon dynamics in different land use systems. The process-based model Land Use Change Impact Assessment (LUCIA) model was applied for future prediction under various climate change scenarios and management strategies.

1.1 Background of study

Terrestrial carbon pools play an important role in the global carbon cycle (Turner et al. 1998). The importance of carbon stocks is to decrease CO_2 emission into the atmosphere, and serve as a way for climate change mitigation from increasing woody carbon stock. The measurement of biomass and productivity of vegetation is considered as one of the goals of the International Geosphere –Biosphere Programme (IGBP) (IGBP, 1998). In most tropical countries, the largest source of green house gas emissions is from deforestation and forest degradation (Houghton, 2012). In South East Asia, expanding global and regional markets are driving the conversion of traditional subsistence agricultural and occupied non-agricultural land to commercial-agricultural purposes (Li et al., 2008; Ziegler et al., 2009; Zhai et al., 2012). The most important conversion is rubber trees substitution of ecologically important primary/secondary forest, and traditionally managed swidden fields. Rubber trees are native to the Amazon basin, the traditional growth regions in SEA are Malaysia, Indonesia and Southern Thailand. The spanning of monoculture rubber plantations is covering southwest China, Laos, Cambodia, Myanmar, northeast Thailand, and northwest Vietnam (Li and Fox, 2012).

In China, Yunnan province is regarded as one of the globally important biodiversity hot spots. Moreover, Xishuangbanna prefecture of Yunnan province maintains the highest biodiversity level in tropical forest (Cao and Zhang, 1997; Myers et al., 2000). Thus, the relevant studies in this region concerning biodiversity conservation, carbon stock estimations, hydrological process analysis have drawn great attention from the public (Zhang and Cao, 1995; Lu et al., 2006; Li et al., 2008; Gao et al., 2009). As one kind of agricultural tree crop, rubber (*Hevea brasiliensis*) produces timber, and other Non Timber Forest Products (NTFPs, e.g. latex) to meet human needs (Killmann and Hong, 2000; FAO, 2001). Since the 1950s, rubber was first introduced to Xishuangbanna, mainly for military usages. In order to provide a suitable habitat for rubber growth, most of the primary forest was cleared. Between 1976 and 2003, rubber cultivated area expanded 10 times, resulting in a sharp decrease of tropical mountain forest. The high commercial profitablitity gained from rubber plantation has prompted its geographical range expansion (Mann, 2009).

Measuring and monitoring terrestrial vegetation carbon stock has achieved great attention. This is as a result of its relevance of quantification of stocks and monitoring terrestrial vegetation, as well as due to fluxes within the global carbon cycle. More importantly, its significance for climate change mitigation from reduced greenhouse gas emission and increased carbon sequestration. There are some studies conducted in Xishuangbanna relevant to rubber plantation's carbon stock assessment, most of them based on conventional ecological surveys to build biomass equations for rubber (Jia et al., 2006; Tang et al., 2009; Song and Zhang, 2010). These studies are always limited by intensive field surveys and are more local and regional based, while few of them took advantage of Remote Sensing (RS) and Geographic Information System (GIS) technology for large scale carbon stock evaluation (Xu et al., 2011) and future scenarios prediction (Li et al., 2008). In addition, there is a need for making use of models to project the potential impacts of environmental change on long-term patterns of forest growth. The results should be reasonably accessible to forest mangers (Wang et al., 2013). However, the present models applied in rubber-based system were constrained by its application geographical scale, and the difficulty to transfer tree or stand level assessment into landscape level. Here the challenge mainly arises from the necessity of spatially explicit information to represent driving variables that have an impact on the landscape (Ditzer et al., 2000; Tickle et al., 2001 a,b).

1.2 Historic distribution and current expansion of rubber plantations

Rubber originally grew in humid tropical regions, with a high annual average temperature of around 28 °C, a total annual precipitation varying between 1400-4000mm, and humidity ranges from 67% to 82% (Priyadarshan, 2003). A world map showing the principal rubber-producing regions of the world in 1916 (Figure 1.1). Rubber plantations have been developed in the Federal Malay States (now Malaysia), Straits Settlements, Java, Sumatra, Ceylon, southern India, Borneo, and Dutch and British Guiana. Some rubber is also produced in the various colonies of west and central Africa, Philippine Islands, and Trinidad (Brigham and McFarlane, 1916). The commercial cultivation of rubber trees has expanded to other Southeast Asian countries that lead in world natural rubber production (Chan, 2000; Figure 1.2). The suitable natural cropping climates for rubber in the mainland of South East Asia include portions of southern Thailand, southeastern Vietnam, and southern Myanmar, other new expansion regions mainly located in Montane Mainland Southeast Asia

(Fox and Vogler, 2005). Warren-Thomas et al. (2015) reported the expansion of rubber plantations occurred within four biodiversity hotspots (Sundland, Indo-Burma, Wallacea and the Philippines) (Myers et al., 2000); within multiple biogeographic realms and ecoregions (Olson et al., 2001); contained various cultivation practices from monoculture to rubber agroforestry (Fox and Castella, 2013). This posed important impacts on existing rubber-dominated landscapes, to meet the requirement of yield maintenance and ensure vigorous biodiversity and ecosystem sustainability.

With increasing worldwide natural rubber consumption and economic development, in the 1950s, the Chinese government initiated the "Decision on Cultivating Rubber Trees" for national defense and industrial demands. This strategy promoted the cultivation of rubber plantations in non-traditional environments, expanding as far north as 22° latitude in China (Xu et al., 2005). From 2002 to 2010, rubber cultivation area had an increase of over 175%, and it covered 22.14% of Xishuangbanna's landscape (Xu et al., 2014). The unclear definition of natural forest and plantations in forest management policies also threatens the nature reserves, national protected areas and important reservoir areas (Li et al. 2007; Xu et al. 2009; Zhai et al. 2014).

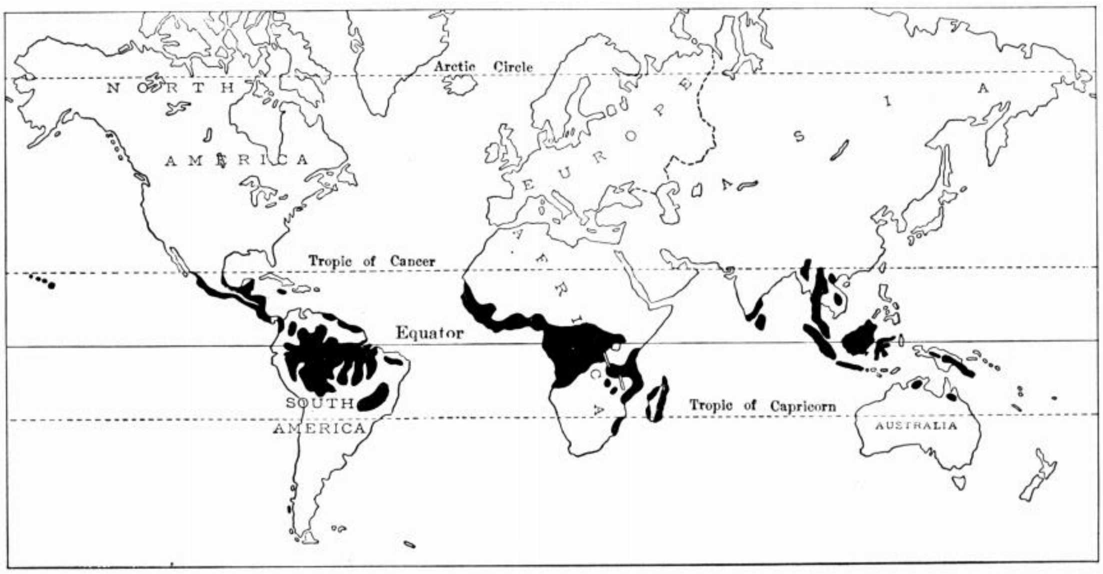

Figure 1.1 Rubber producing regions in 1916. Bidgham and McFarlane (1916), Downloaded from Maps ETC, on the web at: http://etc.usf.edu/maps [map #04730].

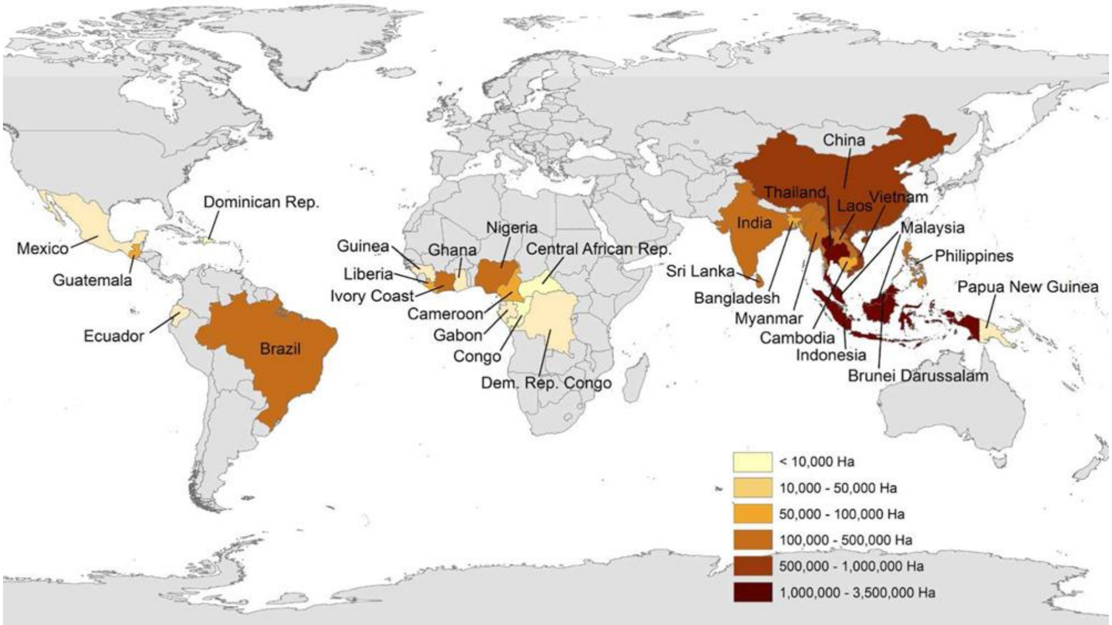

Figure 1.2 Rubber extent in all rubber producing countries, excluding Bolivia for which data was unavailable. Source: Warren-Thomas et al., 2015. Conservation Letters

1.3 Future potential rubber expansion and its impact under climate changes

In order to conduct an effective conservation planning in the context of a rapidly changing environment, it is important to develop good understanding of climate change impacts on regional land use change process (Xu et al., 2009, 2014). Many studies evaluated the future distribution of rubber plantations by analyzing influencing spatial factors under four climate change Representative Concentration Pathways (RCPs) for 2050 (IPCC 2014). The results revealed that almost all mainland SEA countries intended to increase their rubber plantation area in marginal environments. Those regions are located in zones with high vulnerability to typhoons, droughts and frost risks. The side-effects of expansion include: rubber yield decline, regional biodiversity loss and unsustainability of ecosystem service (Ahrends et al., 2015). In the context of Xishuangbanna, the area suitable to rubber plantations growth would expand to nearly 75% of the total area. With the removal of bioclimatic barriers for further expansion, it will pose pressure on biodiversity both within and outside of protected areas (Zomer et al., 2014). Generally, projected climate change in Xishuangbanna will potentially interact with land use change processes to exacerbate the impact on terrestrial ecosystems, biodiversity and agricultural production (Yu et al., 2006).

There are also studies concerning rubber plantation growth response to climate change. The historic meteorological data was analyzed in relation to rubber phonological response and latex production. The results revealed that with an increase of rainfall during summer, this can cause more leaflets falling due to the infection of powdery mildew disease (Johnston, 1989). This infection might cause twice defoliation and results in poor photosynthesis activities (Rakchum, 2010). Climate change may contribute to fluctuated annual rainfall, enlarge annual minimum and maximum temperature difference, and prolonged drought/flood events, influencing rubber tree growth and latex production (Sdoodee and Rongsawat, 2012; Nguyen and Dang, 2016). However, those studies relied greatly on the available historic meteorological data, and simultaneously measured rubber growth and latex yield, constraining their results transformability to other rubber cultivated regions. The integrative impacts from climate change and regional management activities on rubber trees growth, are still not fully understood.

1.4 Carbon sequestration potential of rubber plantations in Mountainous Mainland Southeast Asia

1.4.1 Carbon sequestration in various rubber cultivation regions

The components of the carbon budget in rubber-based systems include above ground carbon stocks (e.g. stems, branches, leaves), below ground carbon stocks (e.g. tap roots, coarse roots, fine roots), soil organic carbon, understory vegetation and litter carbon stock. The collected latex and green house gases should also be counted in the carbon sequestration potential (Blagodatsky et al., 2016). In rubber growing regions, the classification of rubber management schemes could be divided as: monoculture, intercropping-temporary, intercropping-permanent with short rotations, intercropping-permanent with long rotations, and mixed system-permanent as “jungle rubber” (Gouyon et al., 1993; Langenberger et al., 2017). The structure of old jungle rubber is similar to that of a secondary forest, with rubber trees holding the ecological place of pioneer trees found in spontaneous secondary forests in the area. Clough et al. (2016) reported a higher carbon storage potential of jungle rubber than other rubber plantation systems. Within 25-year rotation length, the reported maximum above ground carbon stock of monoculture rubber plantations ranged from 49-174 Mg C ha^{-1} (Wauters et al., 2008; Tang et al., 2009; Song and Zhang, 2010; Petsri et al., 2013). Several studies suggest that modifications in the microclimate as a result of intercropping have beneficial effects on photosynthesis and growth of rubber (Nugawela, 1989; Rodrigo et al., 1997; Rodrigo et al., 2000; Rodrigo et al., 2001b; Senevirathna et al., 2003). Up to date, the comparison of rubber plantations carbon sequestration potential with other land use/cover types, or among various rubber management schemes are still limited. The reasons emerge from the great difference of rotation length/succession stage for land use/cover types (van Noordwijk et al., 2002; Hairiah et al., 2011); the field sampling might fail to represent high intra-class variability among rubber trees of different ages, clone types and under various soil conditions (Wauters et al., 2008). In addition, the different management strategies, such as planting density among smallholders’ rubber plantation will contribute to variance (Naji and Sahri, 2012). In order to conduct a complete carbon budget assessment in the context of afforestation and reforestation activities (GPG LULUCF IPCC, 2004), a more practical, standard and cost-effective carbon stock evaluation approach is required for rubber cultivating countries.

1.4.2 Latex production and importance for local livelihood

The role of natural rubber cultivation is as an important source of income for rural communities in South East Asia. Latex is a gummy white liquid consisting of a mixture of water, hydrocarbons, resins, oils, proteins, acids, salts, and sugar (FAO, 2013). Rubber trees are being tapped starting from 7 years if they grow under a suitable environment. The latex from the lower part of the trunk has a high commercial value which can assist rural communities in socioeconomic development; additionally, the trunk is a source of timber and wood, while its branches are now being used for firewood and pegs (Vongkhamheng et al., 2016). Rubber plantations are mainly belonging to state-farm plantations or smallholder farm plantations. The latex yield in the former is considerably larger than the later. The reasons primarily are due to good management practices with relative lower planting density (around 495 trees ha^{-1}); better investment in equipment; a training and fertilization; applying shielding latex collection during rainstorms (Yi et al., 2014a).

To improve latex production, many studies attempt to find determining factors. Nguyen and Dang (2016) explored the interactive effects among soil type, nature rubber clone types, and temperature on latex productivity. They hypothesized that minimum temperature influenced latex flow and mean temperature affected latex regeneration. The temperature importance was also confirmed from studies of Golbon et al. (2015). Besides this, Yu et al. (2014) reported the great diurnal temperature difference contributed to high yield even in marginal regions (such as Jinghong farm). Yi et al. (2014b) firstly upscaling rubber yield into a large landscape, by linking with topographic, climatic and soil factors they explored the Net Present Value spatially explicit distribution of rubber plantations. This provides the possibility for long-term land use strategies development and offers guidance for appropriate site selection (Chen et al., 2016). With the increasing ambient temperature, how natural rubber productivity responds to warmer temperature has become a major concern.

1.4.3 Carbon trading market and impacts on ecosystem services

It is well known that environmental services include: 1) immediate and tangible benefits, such as timber production, provision of water, food production; 2) intangible benefit, such as biodiversity preservation, nutrient cycling, water regulation, soil erosion control and climate stabilization through carbon storage (Costanza et al. 1997). As one crucial service from ecosystems, carbon stock also attracts more attention to its economic profit. In the current situation, the government provided eco-compensation for maintenance of natural forests, is lacking of competition in front of the benefit from forest transition into mono-cultural rubber plantation (Li and Yuan, 2008). Moreover, the market based incentives, such as REDD+ and clean development mechanism also face threats when facing the high income from mono-cultural rubber cultivation (Yi et al., 2014a). To defend forest resources in South East Asia, scenarios of selective logging and forest-to-rubber conversion were explored. The results indicated policy initiatives were urgently need: 1) a rubber sustainability initiative that restricts market access for deforestation rubber and /or offers a price premium for non-deforestation rubber; 2) zero deforestation pledges from major corporate rubber consumers; 3) governmental regulatory or economic incentives for forest conservation (Warren-Thomas et al., 2018). In Xishuangbanna, in order to test the robustness of market based ecosystem payments, different assumptions of land use scenarios were simulated by using a spatially explicit model for rubber plantations' Net Present Value (NPV), carbon sequestration and seed plant biodiversity (Yi et al., 2014b). The results showed conservation oriented scenarios (COS) could gain 57% more carbon and 71% more biodiversity than an economic oriented scenario (EOS), more importantly, these scenarios will enhance other ecosystem services to obtain more ecosystem benefits. The reduced NPV of rubber still cost less when compared with the expense to recover this reduced NPV (Yi et al., 2014b). Engel et al. (2008) proposed that the monetary benefit can be the dominant reason to determine landowners land use behavior. With the decreasing dry latex price from global market, it is still promising to expect the constraint of current rubber expansion, and reforest action of low profit rubber plantations by market based ecosystem payments.

1.5 Modelling the rubber plantation growth and latex productivity

1.5.1 Research gaps and challenges in existing empirical and process-based modeling of rubber growth

The increase of CO_2 in the atmosphere would lead to increased productivity where growth is not limited by other factors such as soil fertility or water availability (Hyvönen et al., 2007; Ainsworth and Long, 2005). The stimulated growth of forest trees are serving as carbon sink to remove carbon from the atmosphere (Lugo and Brown, 1992). The high gross primary productivity and large area of tropical forests indicates that even a small shift in the balance between growth and respiration in these ecosystems would have major implications for the global carbon cycle (Grace et al., 1995; Grace, 2004). However, process-based models do not always include the CO_2 enrichment effect, particularly those models based on empirical data (e.g. Hybrid model). Therefore, those models are likely to yield underestimation of forest productivity. Other uncertainties from elevated CO_2 towards productivity are the extent to which models could down-regulate of plant photosynthesis, and whether models take into account interactions between temperature and CO_2 (Medlyn et al., 2011). Besides this, the temperature rise might increase evaporation and thereby cause increased cloudiness. Light, as one of the regulators of growth, recruitment and mortality, is limited by cloudiness and by competition from neighboring trees. Currently, prediction of how clouds will change is still a weak point in many climate models (Fearnside, 1995). A number of process-based global NPP (Net Primary Production) models do not explicitly calculate PAR, but compute a leaf area index (LAI) and then convert to PAR by functional relationship (Ruimy et al., 1999). At present, the fine resolution of spatial and temporal variations of absorbed PAR is still a challenge, although efforts were made in many studies (Van Laake and Sanchez-Azofeifa, 2004, 2005). Also other environmental factors which influence canopy phenology were not considered in previous models, such as soil moisture, atmospheric droughts (Eamus and Prior, 2001; Sopharat et al., 2014), and annual cycle of solar radiation intensity (Yeang, 2007; Borchert et al., 2015). Stated from

Boote et al. (2013), the current limitation of many crop models is that they did not consider atmospheric constraints on transpiration. This can result in overestimation of transpiration and root water update, moreover, a further overestimation of photosynthesis activities. Those models include CROPWAT (Allen et al., 1998) and WaNuLCAS (Van Noordwijk and Lusiana, 1999). Therefore, the improved rubber trees canopy CO_2/H_2O fluxes simulation model soil-vegetation-atmosphere transfer (SVAT) made consideration of rubber trees canopy structure, and proved the application in advising optimum rubber trees spacing to achieve high primary productivity and water use efficiency (Kumagai et al., 2013).

Although process-based models still have various limitations, they are increasing applied in projections of forest growth and productivity under climate change and serving as decision making tools. Such as 3-PG (Almeida et al., 2009; Almeida et al., 2010), Triplex (Wang et al., 2012); 4C (Reyer et al., 2014); PnET (Gustafson et al., 2017), BIOME-BGC (Eastaugh et al., 2011) and FORECAST (Seely et al., 2015). Previous forest models could not fulfill the requirement for detailed latex production simulation, which made relevant management guidance (tapping frequency, tapping days) difficult. Few of them link with spatially explicit maps, this caused challenges in landscape level decision making.

1.5.2 Uncertainties evaluation in various spatial scale for biomass estimation

Plant biomass estimation could be conducted from plant, plot, landscape and regional level. Understanding potential sources of uncertainty during live tree biomass estimation can improve future estimates and especially aid interpreting ecological complexity (Harmon et al., 2007). The uncertainty assessment plays a broader role in risk analysis (Bartell et al., 1992), decision support (Kangas 2010), method evaluation (Lauenroth et al., 2006), and ecological modeling (Wu et al., 2006). To meet the research limitations in classical analytical error- propagation methods, and lack of computational power and standard practice, Harmon et al. (2015) proposed a general framework for considering uncertainty as an evaluation metric in synthesis science. The uncertainties could be defined as: 1) measurement uncertainty always defined by precision and accuracy during experimental measurement; 2) sampling uncertainty is reflected from mean and variance, to represent natural variation in space and time; 3) model uncertainty is related to the transformation of measurement into other variables of interest (e.g. predict biomass from tree height or DBH); 4) the model selection uncertainty is reflecting the potential variation from using different form of the relationships in a model. They further argued the most challenging aspect of uncertainty in synthesis involves model selection. However, this part was always ignored in most studies. Especially in ecological phenomena or processes that are difficult to measure, such as net primary production, heterotrophic respiration, net ecosystem production, and net ecosystem carbon balance. For rubber-based systems, the sources of uncertainties for carbon stock assessment could be divided into tree level, plot level and landscape level. Caution should be paid when upscaling to regional or national scale evaluations (Blagodatsky et al., 2016).

1.6 Justification of study

In the context of this study, the main purpose is providing a comprehensive carbon stock assessment by integrating high spatial resolution and multi-temporal satellite data with conventional field surveys. In order to better understand future carbon stock changes and rubber yield under a global warming background, the explicit spatial model Land Use Change Impact Assessment (LUCIA) will be applied and the simulation result of this study could provide local decision makers with a baseline for sustainable land use management (Figure 1.3).

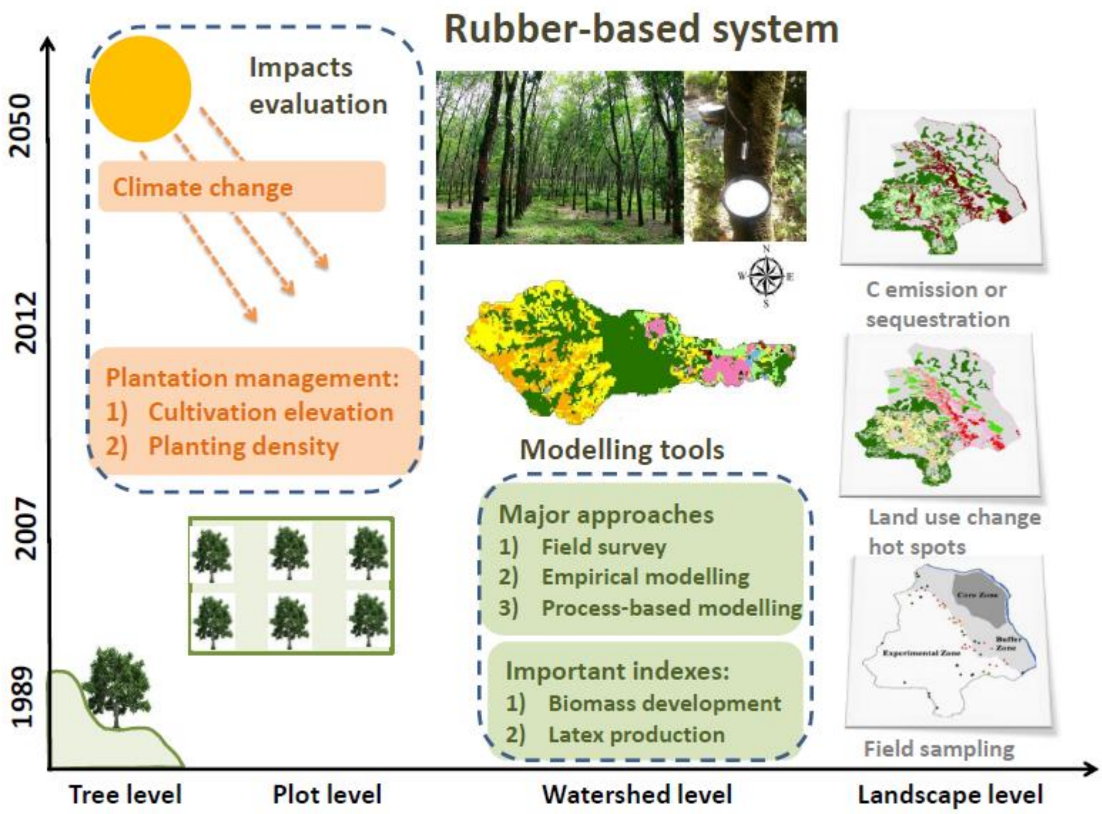

Figure 1.3 Basic framework design of the present study. Figure demonstrates the consideration of spatial and temporal evaluation.

1.6.1 Guiding hypotheses

The guiding hypotheses addressed in this thesis are:

- Rubber expansion has an impact on regional landscape carbon stock distribution; it contributes to carbon loss when substituting tropical forest;

- The Rapid Carbon Stock Appraisal (RaCSA) approach could act as an effective carbon accounting tool in mosaic landscapes;

- The newly established allometric equations are suitable for rubber plantations distributed in mountainous regions, covering various elevations, clone types and stand age;

- LUCIA could be applied in dynamic evaluation of rubber tree physical growth and making future projections;

- The regional management has a larger impact on rubber tree biomass development and latex production, than large scale climate change effects.

1.6.2 Case study objectives

The overall aim of the presented study was to examine the impact of rubber cultivation on local carbon stocks by using a dynamic and spatially explicit modeling approach. The following specific objectives were examined:

- Can rubber plantations maintain a high carbon sequestration potential under land use change? What are the spatial-temporal changes of carbon stocks in Naban River Watershed National Nature Reserve during 1989-2013?

- Are there any existing allometric equations suitable for newly expanded rubber plantations in marginal areas? Which environmental factors act as determining variables for rubber plantations carbon stock distribution?

- Can process-based modeling combined with ground surveys be used to support decision making with reference to sustainable rubber plantation management? How to find a balance between carbon sequestration potential and economic benefits?

1.6.3 Structure of thesis

This doctoral work is conceived as a cumulative thesis, where each research chapter is a journal article. In Chapter 2, the RaSCA was applied in a Man and Biosphere reserve for carbon balance accounting during 1989-2013. Chapter 3 focuses on rubber-based systems, in which biomass allometric equations that suitable for mountainous landscapes/marginal areas were established. The dominant influencing environmental factors were tested to check their impact on rubber plantations carbon stock. Chapter 4 describes how to integrate ground surveys with process-based modeling for environmental impact assessment. The model results on biomass development and latex production offer the reference of local decision making. The effects from local management, such as rubber cultivation elevation and planting density, as well as various climate change scenarios were assessed. The general discussion (Chapter 5) makes the future outlook for research gaps and challenges. The role of modeling and the added value of stakeholders' involvement could facilitate synergies for sustainable rubber cultivation in the Great Mekong Region.

Chapter 2

Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China

Chapter 2 Land-use change impact on time-averaged carbon balances: rubber expansion and reforestation in a biosphere reserve, South-West China[1]

Xueqing Yang[a,b,e], Sergey Blagodatskiy[a], Melvin Lippe[a,f], Feng Liu[c], James Hammond[d,g], Jianchu Xu[e], Georg Cadisch[a]

[a] *Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Stuttgart, Germany*

[b] *Key Laboratory of Economic Plants and Biotechnology, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China*

[c] *Bureau of Naban Watershed National Nature Reserve, Yuanlin alley 19#, Jinghong, 666100, China*

[d] *World Agroforestry Centre (ICRAF), Nairobi 00100, Kenya*

[e] *World Agroforestry Centre (ICRAF), China & East Asia Office c.o. Kunming Institute of Botany, Heilongtan, Lanhei Road No.132, Kunming 650201, China*

[f] *Institute of Crop Science, Department of Biobased Products and Energy Crops, Früwirthstr. 23, Stuttgart 70593, Germany*

[g] *School of the Environment, Natural Resources and Geography, Bangor University, Bangor, Gwynedd LL57 2UW, United Kingdom*

[1] **This chapter has been reprinted from:**
Yang, X.Q., Blagodatsky, S., Lippe, M., Liu, F., Hammond, J., Xu, J.C., Cadisch, G., 2016. Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China. Forest Ecology and Management 372, 149-163. (http://dx.doi.org/10.1016/j.foreco.2016.04.009

The original publication is available at:
https://www.sciencedirect.com/science/article/pii/S0378112716301657

Abstract

The expansion of rubber plantations (*Hevea brasiliensis* Müll. Arg) is a major driving force for deforestation and forest degradation in mountainous South-East Asia. In China, the unclear distinction between natural forest and commercial plantations in land use classification system has permitted the expansion of rubber plantations into protected forest areas of nature reserves. However, the impact of such land-use changes on landscape carbon balances within nature reserves has rarely been investigated, and particularly lacking has been consideration of different land use types rotation lengths for accurate long term carbon estimates. The Naban River Watershed National Nature Reserve (NRWNNR), Xishuangbanna, China, was selected as a case study location. Carbon stocks were evaluated using the Rapid Carbon Stock Appraisal (RaCSA) method based on tree, plot, land use and landscape assessments, integrating field sampling with remote sensing and GIS technology. Six dominant land use systems were surveyed: lowland forest (<800 m above sea level), highland forest (>800 m above sea level), lowland rubber, highland rubber, bush and grassland and agricultural crops. Land use type-specific time-averaged carbon stocks (C_{ta}) were then used for the landscape level upscaling. The time-averaged carbon stocks of lowland and highland rubber plantations were 58 Mg C ha^{-1} and 28 Mg C ha^{-1} respectively, showing larger carbon sequestration potential than non-forest land use types (agricultural crops, bush and grassland) but much lower than C_{ta} of natural forest (156 –185 Mg C ha^{-1}). Sensitivity analysis of time-averaged carbon stocks variability showed that forest C stocks have the largest influence on landscape carbon balance. Time series analysis of land-use and land-cover maps (1989, 2007, 2012) demonstrated that during 23 years, the whole landscape of the nature reserve (26574 ha) gained 0.644 Tg C. Despite rubber expansion, biosphere zoning strategy (i.e. experimental, buffer, core zones), and reforestation activities conducted in NRWNNR were able to enhance the carbon stocks.

Keywords

Rubber plantations, Rapid Carbon Stock Appraisal, time-averaged carbon stocks, mosaic agricultural landscape, carbon sequestration

2.1 Introduction

On a global-scale, tropical deforestation is estimated to have released 1-2 Pg C yr^{-1} during the 1990s, representing 15-25% of annual global greenhouse gas emissions (Malhi and Grace, 2000; Fearnside, 2000; Fearnside and Laurance, 2003, 2004; Houghton, 2005). According to Baccini et al. (2012), during the period 2000-2010, up to 1 Pg C yr^{-1} was released from tropical deforestation and land-use change, thus continuing to make a substantial contribution to the global C budget. In South East Asia, 65% of tropical forest degradation can be mainly attributed to land-use change trajectories towards intensified agricultural crops (FAO, 2009). For example, in the tropical regions of China, the current major driver of deforestation is the conversion to rubber plantations, a trend also observable across many parts of South East Asia (Ziegler et al., 2009; Xu et al., 2005; Xu et al., 2013). At present, rubber plantations in Montane Mainland Southeast Asia (MMSA) cover an area of more than 2.1 million ha, based on 2009 and 2010 satellite data and sub-national statistical data, from which with about 20% (424,000 ha) being located in the prefecture of Xishuangbanna, Yunnan Province, China (Li et al., 2008; Li and Fox, 2011; Xu et al., 2013; Fox et al., 2014). The high rate of rubber expansion threatens local ecosystem services, such as carbon sequestration and biodiversity (Li et al., 2007; Hu et al., 2008; Xu et al., 2009; Fu et al., 2010; Tan et al., 2011), and competes for land use with nature reserves designed to protect such ecosystem servies. This has led to a lack of landscape connectivity, threating the ecosystem integrity of nature reserves (Liu et al., 2014).

The loss of important nature reserve habitats is further aggravated by the land use classification system based on FAO’s Global Forest Resources Assessments (FRAs), which defines rubber plantations as “planted forest” (Keenan et al., 2015). Many scholars have already criticized this definition. For instance, the central government of China initiated the Sloping Land Conversion Program (SLCP) in 1999, with the aim to restrict agricultural production on steep sloping and marginal lands and to foster reforestation (Xu et al., 2006), but the unclear distinction between natural forest and commercial forest plantations such as rubber acted as a driving force for uncontrolled expansion of market-oriented rubber plantations, including the invasion into protected forest areas in nature reserves (Xu et al., 2011; Zhai et al., 2014).

Against the backdrop of such widespread rubber expansion, the degree to which rubber plantations could serve as long-term carbon sinks is an important question. Cheng et al. (2007) noted that fast-growing rubber plantations could accumulate carbon more rapidly than slow-growing natural forests up to the time of harvest (30 years). Song and Zhang (2010) stated that rubber plantations located in suitable areas at elevations lower than 800 m showed greater carbon sequestration potentials than tropical forests within the same life time period. Nevertheless, for long-term carbon storage and climate change mitigation, slow-growing forests would be more preferable because of the persistence of the large living carbon stocks, such as above-ground biomass (Kirschbaum, 2006). Recent evidence from biometric estimations and eddy covariance methods further indicated that rubber plantations do not always serve as a carbon sink, especially if deforestation of previous primary forests was taken into account during the whole rotation length (Song et al., 2014). Rubber plantations are usually harvested before reaching the maximum biomass production potential, thus the rotation length matters for various carbon pools to regain the carbon stock of the pre-disturbance stage (Nizami et al., 2014).

Current available protocols for assessing carbon balances at landscape scale include biome averages, process-based modeling, forest inventory surveys, eddy covariance and remote sensing techniques, each with unique advantages in different aspects of cost, accuracy and geographic scale (Gibbs et al., 2007; Qureshi et al., 2012). However, few of them are practical in a cost-effective and time-efficient manner for guiding local resource management in developing countries, with the further risk of incomparability and inconsistency between selected methods. In contrast, the Rapid Carbon Stock Appraisal (RaCSA) approach is a multi-disciplinary carbon accounting assessment method, which makes use of farmers' key-stakeholders groups local knowledge, integrating ground truth point measurement data with geo-spatial analysis to provide advice for land use management (Hairiah et al., 2011). The RaCSA method combines several carbon stock evaluation protocols into a single assessment framework, aiming to decrease the uncertainties from using different methods. The RaCSA approach also accounts for the time dynamics of land use systems including tree regrowth and harvesting, which is especially suitable for mosaic agricultural landscapes such as rubber plantation-forest landscapes (Hairiah et al., 2010; van Noordwijk et al., 2002). The carbon accounting approach of RaCSA is based on the 'time-averaged carbon stock (C_{ta})' approach. The C_{ta} of a land use type is determined by the average carbon stored in that land use system during its rotation time (Palm et al., 2000), taking into account tree or plant establishment/regrowth and harvesting. This allows the comparison of land use systems that have different rotation lengths. If there is no active process of intensification or adoption of new practices, we assumed that all phases of the life cycle are represented spatially in accordance with their proportion in the total life cycle. Hence, this method is easier to implement for field-based assessments compared to other accounting methodologies, such as 'gross net accounting', 'net-net accounting', and 'net accounting with negotiated baselines' (Cowie et al., 2007). It directly simplifies the accounting process as the change in time-averaged stocks links directly to human land use decisions, and corresponding land use area. The approach has been widely used in carbon stock evaluation models, such as FALLOW (van Noordwijk et al., 2008; Lusiana et al., 2012) or CO_2FIX (Rodriguez-Loinaz et al., 2013).

With the development of Remote Sensing (RS) and Geographic Information System (GIS) technology, it is possible to complement traditional ground-based surveys with a more effective and convenient approach to upscaling. Recently remote sensing images have been widely used for rubber plantation area mapping (Ekadinata et al., 2004; Suratman et al., 2005; Wasana, 2010; Dong et al., 2012; Li and Fox, 2012; Senf et al., 2013), rubber wood volume estimation (Jusoff and Yusoff, 2009), rubber stand age estimation (Chen et al., 2012), rubber plantation phenology monitoring (Dong et al., 2013), and leaf area index dynamics (Chen et al., 2015). By integrating different GIS tools, it is further possible to conduct land suitability analysis of rubber plantation distributions under current (Nguyen et al., 2015) and future climate change (Zomer et al., 2014; Ahrend et al., 2015). These satellite assisted methods also have the potential to provide timely monitoring of carbon stock components over large areas in both geographical and temporal scale (Qureshi et al., 2012). Nevertheless, detailed ground truthing data are required for carbon sequestration or emission assessments using RS or GIS (DeFries et al., 2007). Therefore, integrated approaches like RaCSA are preferred when conducting spatial and temporal evaluations of landscape level carbon dynamics.

Ground truth-based carbon stock assessments of rubber plantations in Xishuangbanna were already quantified in several studies (Jia et al., 2006; Bao et al., 2008; Tang et al., 2009; Song and Zhang, 2010; Song et al., 2014). However, most of these studies were either carried out at tree-level or plot-level, and at different geographical locations, yielding widely different estimates (e.g. the averaged values were ranging from 15 Mg C ha^{-1} to 90 Mg C ha^{-1}), bringing into question the reliability of the derived landscape-level carbon sequestration potential estimates of rubber plantations and other land use types. This is important to consider because carbon stock differences could arise from the variability of specific site properties, such as slope, aspect, soil fertility, climatic conditions and historic land use management. In addition, in tropical agricultural landscapes, the spatial variability of different rotation stages will be a further reason for under- or over-estimation of carbon stocks (Kuyah et al., 2012). Many of these uncertainties could be eased if the change in C_{ta} was used for comparison among different land use types (Cowie et al., 2007). Moreover, in the case of Xishuangbanna, almost no study to date simultaneously assessed the complete set of carbon pools for different land use types at landscape scale (namely aboveground biomass, belowground biomass, necromass, and soil), which is necessary for a complete carbon budget assessment in the context of afforestation and reforestation activities (GPG LULUCF IPCC, 2004).

Against this background, we attempted to address the following questions by applying the RaCSA approach in our study: (1) Can rubber plantations compensate for carbon losses due to deforestation? (2) How do previous land use types affect the carbon balance after establishment of rubber plantations? (3) Can managed nature reserve areas still gain carbon during rubber plantation intensification? To answer these questions, the Naban River Watershed national Nature Reserve (NRWNNR) was chosen as a case study area, where various land use types could be observed at different elevations and rotation ages. The impact of elevation on rubber plantation was evaluated by further splitting rubber plantation areas into lowland and highland rubber plantation land use classes. A comprehensive spatial-temporal evaluation of carbon stock change patterns across the whole landscape was achieved by linking C_{ta} with information from land-use/land-cover maps over a 23 year period (1989-2012). These results can provide reference data for landscape carbon accounting in other South East Asia regions.

2.2 Material and methods

2.2.1 Study site

The NRWNNR is located in the Dai Autonomous Prefecture of Xishuangbanna, southern Yunnan, China (Figure 2.1). It is a ‘Man and Biosphere reserve’ according to the UNESCO concept and became a local nature reserve in 1991, and a national nature reserve in 2000. The total protected area is 26,660 ha (22°04′- 22°17′ N, 100°32′-100°44′ E) within an elevation range 539-2304 m. The area has distinct dry (November-April) and rainy seasons (May-October). The annual rainfall varies from 1200-1700 mm, and the annual mean temperature range is 18-22 ℃ (YEPB, 2006).

The historic dominant vegetation types are: (1) tropical seasonal rainforest, (2) tropical montane evergreen broad-leaved forest, (3) deciduous broad-leaved forest, (4) bamboo forest, (5) shrub and grassland and (6) agriculture land (Tao, 1989; YEPB, 2006; Zhu, 2007). Based on YEPB (2006), the percentage of these dominant vegetation type area in nature reserve is 30%, 12 %, 7 %, 10 %, 21 % and 9 % respectively. Currently, rubber plantation is emerging as a new dominant vegetation type in NRWNNR. Initiated by high economic benefits obtained from latex production, the area of rubber plantations increased rapidly, quadrupling between 1989 and 2000, to 924 ha (Tao, 1989; YEPB, 2006). In NRWNNR, main soil types are Latosols distributed below 800 m, while lateritic red soils are located between 800-1500 m, and mountain red earths at locations higher than 1500 m (YEPB, 2006). According to FAO classification, all three soil types are Ferralsols with different contents of iron oxides (Apel, 1996), whereas minor soil types include calcaric soils and purple soils (YEPB, 2006), equivalent to Regolsols in the World Reference Base for Soil Resources (FAO/UNESCO, 1998).

The nature reserve is sub-divided into three functional zones: the core zone (3900 ha), the buffer zone (7100 ha) and the experimental zone (15800 ha). The core zone is strictly protected and only limited ecosystem monitoring activities are allowed, providing crucial habitats for endangered and endemic species. Within the buffer zone, local villagers are allowed to perform agricultural activities, with the prerequisite to not harm the ecosystem and environment. This area also allows for establishment of demonstration sites for research activities, and breeding gardens for endangered species. The experimental zone is designed for production purposes only, and is larger than the other two zones, providing further opportunities for agricultural, forestry and animal husbandry (Tao, 1989). During the 1980's, the household contract responsibility system was implemented in NRWNNR, with the introduction of rubber plantations considered as a key innovation in land usage. Rubber plantations are mostly distributed in the buffer and experimental zones and became a major income for local Dai, Hani, Lahu and Yi people. Rubber expansion has been linked to negative environmental impacts on local biodiversity, water balance and carbon stock due to the transition from the forest to rubber-based land use systems (Li et al., 2007; Langenberger et al., 2008; Bao et al., 2008). Other common crops in NRWNNR include: paddy rice (*Oryza sativa* L.), maize (*Zea mays* L.), potatoes (*Solanum tuberosum* L.), sugarcane (*Saccharum sinensis* Roxb), dragon fruit (*Hylocereus undatus* (Haw.) Britton & Rose), lychee (*Litchi chinensis* Sonn.), banana (*Musa x paradisaica* L.), and tea (*Camellia Sinensis* (L.) Kuntze).

Figure 2.1 Landscape view of NRWNNR, including (a) Dai minority village located in the valley of nature reserve; (b) mountain occupied with rubber plantations, with mosaic age distribution; (c) reforestation from bush and grassland; (d) paddy rice is important agricultural crop for local people.

2.2.2 Rapid Carbon Stock Appraisal

In the context of the presented study, the RaCSA carbon stock accounting methodology was customized from Hairiah et al. (2011) as shown in Figure 2.2. The major steps of RaCSA are described below.

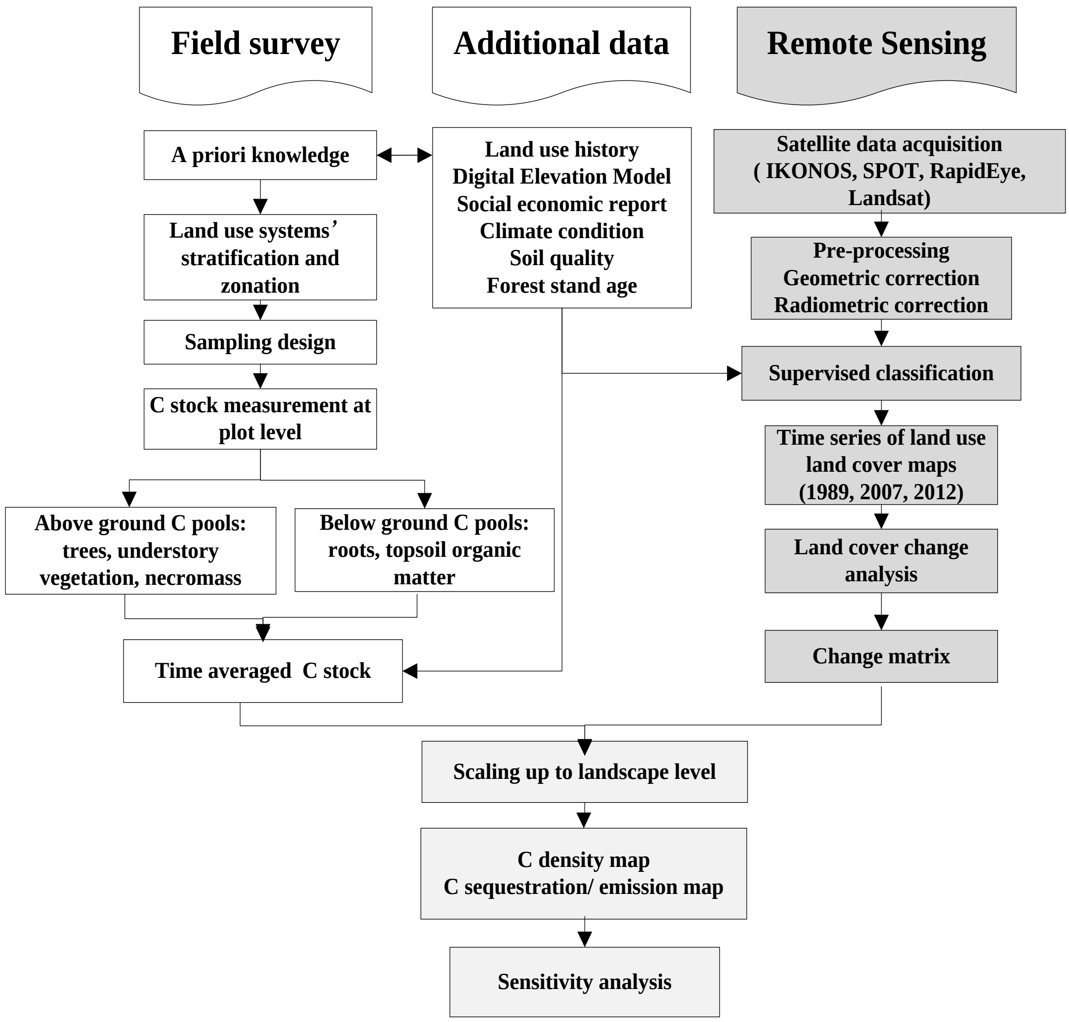

Figure 2.2. Methodology diagram of the current study, adapted and revised from Hairiah et al. (2011), with time-averaged C stock referring to above ground C stocks only.

2.2.2.1 A Priori knowledge collection

Based on available reports, documentary information, and land-use/land-cover maps from a previous project "LILAC: Living Landscapes China" (http://lilac.uni-hohenheim.de/en/index.php), as well as other conducted studies in NRWNNR, a basic understanding of this region's land use history, biodiversity condition, soil fertility and rubber related socio-economic issues was obtained (Bao et al., 2008; Mo et al., 2011; Xie et al., 2012; Cotter et al., 2014). According to reviewed sources, forest degradation caused by rubber expansion already had a negative influence on local forest resources. The high economic return from latex production also greatly changed local farmers' cultivation activities.

2.2.2.2 Sampling design

Five land use types were chosen for carbon stock evaluation: forest, rubber plantation, bush and grassland, agricultural crops and other land use (including settlements and water bodies). The positions of sampling plots in the landscape are shown in Figure 2.3, and methods for data collection are summarized in Table 2.1. According to the sampling scheme proposed by Markum et al. (2013) for forest carbon stock evaluation, we surveyed permanent forest plots in the nature reserve (total 16 plots distributed in experimental and buffer zone), namely: tropical rainforest (two plots), tropical seasonal rainforest (four plots), broadleaved deciduous forest (two plots), seasonal evergreen broadleaved forest (four plots), montane rainforest (two plots) and mingled forest with bamboo (two plots). Here the mingled forest with bamboo stands for mixed structure of bamboo and trees (e.g. *Garruga pierrei*, *G. pinnata*, etc). For simplification and subsequent comparisons with rubber plantations at the same elevation range, we defined lowland forest as located below 800 metres above sea level (m a.s.l) elevation, which includes tropical rainforest, tropical seasonal rainforest and mingled forest with bamboo, while highland forest is located above elevation ranges of 800 m a.s.l, and consists of broadleaved deciduous forest, seasonal evergreen broadleaved forest and montane rainforest types, respectively. In case of rubber plantations, we identified traditional well suited areas for rubber being below 800 m a.s.l. (lowland rubber, 10 plots sampled) as well as more marginal areas above 800 m a.s.l. (highland rubber, 14 plots sampled). We sampled various stand ages of rubber plantations at both elevations, aiming to cover a full rubber rotation length as currently applied in the study area. Hence, lowland rubber (5 to 35 years) and highland rubber plantations (4 to 25 years) were sampled to calculate C_{ta}. All plots were selected within smallholder plantations and with similar management regimes, the additional stand information, such as clone type, planting density were also recorded. Maize (three plots), banana (two plots) and tea (two plots) plantations were surveyed to represent local annual and perennial agricultural crops in NRWNNR. In addition, bush and grassland (three plots) were also sampled in this landscape. For C_{ta}

estimation, the maximum carbon stock during a rotation should be sampled in each land use type (Hariah et al., 2011). The corresponding rotation length was obtained from interviews with local people from villages nearby the sampling plots, and further confirmed by nature reserve's officers.

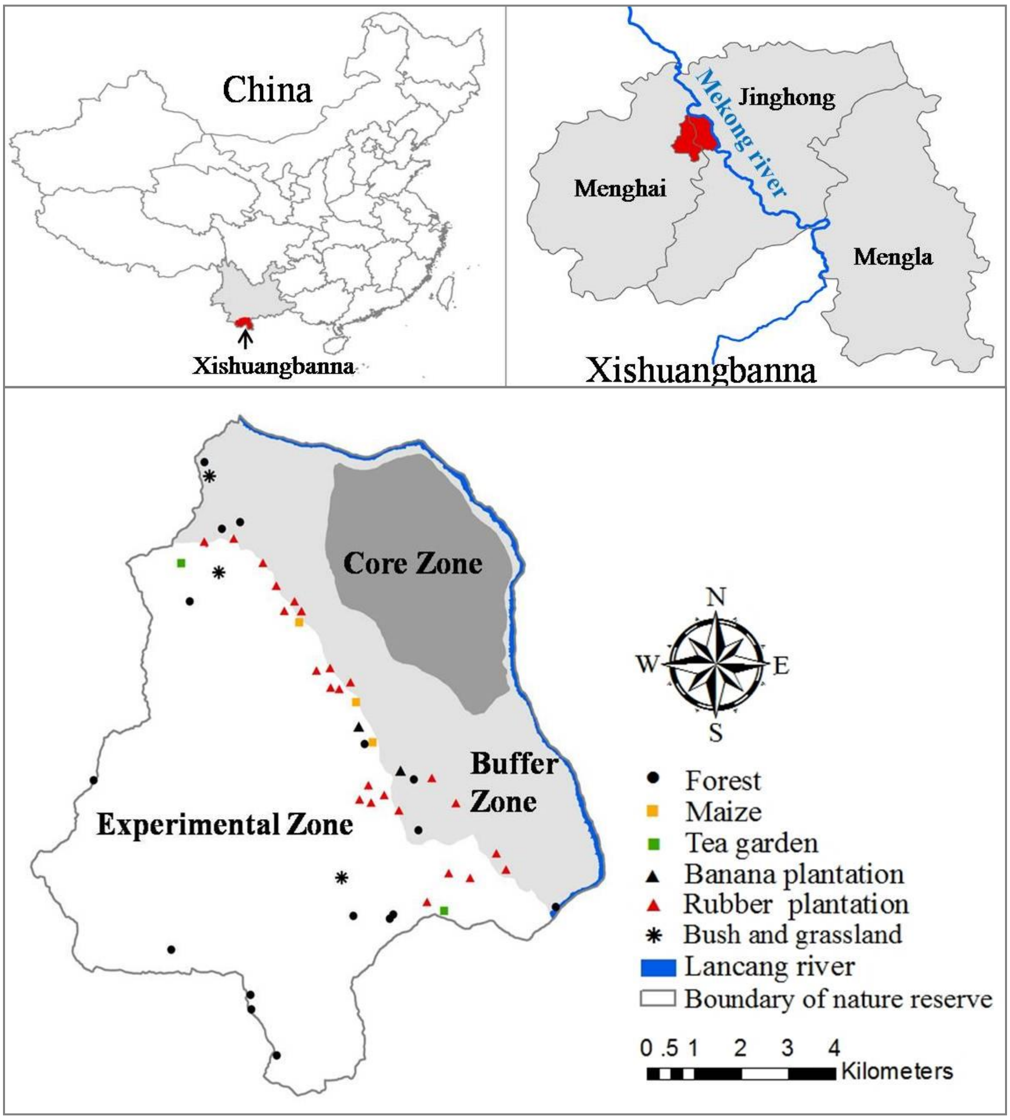

Figure 2.3. The location of the study site, and the functional zones within the Naban River Watershed National Nature Reserve. Sites of sample plots are marked: red triangles represent C stock sample plots in rubber plantations of different stand age and elevation gradients. Forest C stock assessment were conducted within 16 permanent plots of the nature reserve and are represented by black circles. Other sample plots include perennial agricultural crops (tea, banana), annual cops (maize) and dominant bush and grassland.

Table 2.1 Summary of data collection and assessment methods

Spatial scale	Assessment methods	Supporting data	Data source
Tree level	Measuring tree parameters for biomass prediction	Trees with DBH more than 2 cm within plots	Field survey during 2012-2014
Plot level	Destructive and non-destructive methods for four carbon pools	Different land use types within NRWNNR	Field survey during 2012-2014
Land use level	Time-averaged carbon stocks	Different land use types	Field survey during 2012-2014
	Upscaling from plot data using satellite data interpretation and processing	1989 Land-use /land-cover map	Monitoring report of NRWNNR (Tao et al., 1989)
		2007 Land-use /land-cover map	Revised from LILAC[a] project data
		2012 Land-use /land-cover map	Revised from SURUMER[b] project data
Landsc-ape level	Confusion matrix of carbon stocks	1989, 2007 and 2012 carbon stock changes comparison	Land use level data processing

Note: [a]LILAC project: Living landscapes China (http://lilac.uni-hohenheim.de/en/index.php); [b]SURUMER project: Sustainable Rubber Cultivation in Great Mekong Region (https://surumer.uni-hohenheim.de/)

2.2.2.3 Tree and plot level carbon stock assessment

Sampling plots of 30 m x 50 m in the case of forest and 25 m × 20 m plots for tree plantations were demarcated to measure woody plants' diameter at breast height (DBH, 1.3 m above ground) and average tree height. The allometric equations and methods for biomass estimation with corresponding references are displayed in Table 2.2. Within a 25 m × 20 m sampling plot, all woody debris and trunks (unburned), dead standing trees, dead trees on the ground and stumps with a diameter > 5 cm and a length > 0.5 m were sampled. 1 m × 1 m sub-plots (a total of 5 sub-plots within one sample plot, distributed in four corners and one in centre) were used for destructive analysis of understory biomass. Wood density of each wood plant species within forest plots was accessed from the wood density database of ICRAF (http://db.worldagroforestry.org/wd). For sampling plots of perennial crops, DBH of each banana tree was measured while stand age for tea gardens was recorded for upscaling to plot level above ground biomass by applying allometric equation as shown in Table 2.2. Biomass was converted into carbon density by using a factor of 0.5 (IPCC, 1997). Destructive sampling was further conducted within 1 m × 1 m sub-plots for the selected land use types: annual crops, bush and grassland. Soil samples at 0-10 cm, 10-20 cm and 20-30 cm depth were collected at 15 sampling points (5 subsamples per depth and bulked) with a soil auger. For each depth interval, 5 subsamples were pooled in the field to form one composite sample for further analysis. Bulk density samples were collected in a soil pit (0-30cm), with averaged values from three soil ring cores (200 cm^3) for each soil depth interval. Soil samples were dried at 105 ℃ to determine dry weight, and then sieved using a 2 mm mesh to remove any vegetation or gravel present. The soil organic carbon content was determined using a wet oxidation procedure with $K_2Cr_2O_7$ (Nelson and Sommers 1982), the widely used classical approach which requires relatively inexpensive equipment (Yang et al., 2004; Tang et al., 2012; Wauters et al., 2008). Soil carbon stocks (Mg C ha^{-1}) in each depth interval were calculated using equation 2.1:

$$SOC = \frac{\%C}{100} \times BD \times D \qquad (2.1)$$

where *%C* is soil carbon concentration, *BD* is the bulk density (Mg m^{-3}), *D* is the soil depth interval (m). Total topsoil (0-30 cm) carbon stocks were calculated as the sum of three soil depth intervals. Generally, the right of eq. (2.1) needs to be multiplied by a factor 1-P (P represents the proportion of gravel in soil) because the soil bulk density is estimated based on fine soil (< 2mm). In current study, the gravel content of surveyed soil was less than 5%, thus the effect of gravel content in influencing SOC was almost negligible.

2.2.2.4 Time-averaged above ground carbon stock

The majority of existing rotation systems in our study area included rubber-based

Table 2.2 List of allometric equations and methods used to estimate above-ground and below-ground biomass of different vegetation types.

Land use/land cover	**Allometric equation for AGB**	**Source**	**Allometric equation/ root: shoot ratio for BGB**	**Source**
Forest	$W_{AGB} = 0.11\rho D^{2.62}$	Ketterings, 2001	0.235	Mokany et al., 2006
Bamboo	$W_{AGB} = 0.131 D^{2.28}$	Priyadarsini,1999	0.205	Mokany et al., 2006
Rubber plantation	$W_{AGB} = 0.0681 D^{2.6409}$	Van Noordwijk, 2002 Jia et al., 2006	$W_{BGB} = 0.108 D^{1.948}$	Tang et al., 2009
Perennial crops (banana)	$W_{AGB} = 0.030 D^{2.13}$	Arifin, 2001;Van Noordwijk, 2002	0.205	Mokany et al., 2006
Perennial crops (tea)	$W_{AGB} = -14.95 + 56.3(1 - e^{-0.27t})$	Zhang et al., 2013	0.3	Yuen et al., 2013
Annual crops (maize)	Destructive method	This study	0.3	Yuen et al., 2013
Shrubland	Destructive method	This study	1.837	Mokany et al., 2006
Grassland	Destructive method	This study	1.887	Mokany et al., 2006

Note： W: biomass (Mg ha^{-1}), ρ : wood density (g cm^{-3}), D: diameter at breast height (cm), AGB: above ground tree biomass (Mg ha^{-1}), BGB: below ground biomass (Mg ha^{-1}), t: cultivation age (year) systems, tree-based systems, and crop-fallow systems (Supplementary material Figure S2.1 a, b, c). Here we used above ground carbon pools to calculate C_{ta}, because involving plant roots and soil carbon stock can greatly increase upscaling uncertainty and decrease comparability among different land use types.

2.2.2.4.1 Rubber-based system

We conducted intensive surveys of rubber plantations with various stand ages at elevation above and below 800 m a.s.l. In order to simulate rubber tree biomass growth as a function of stand age, most existing studies have used the logistic model (Song and Zhang, 2010; Petsri et al., 2013; Song et al., 2014). Though this choice is one of possible sigmoid functions applicable for the description of tree growth (Zeide,1993), we applied the logistic model in order to get the results comparable with those obtained in previous studies. The growth function was fitted with three parameter logistic equation (Paine et al., 2012), by using dynamic curve fitting function from Sigmaplot 12.0:

$$C = \frac{C_{\max}}{1 + me^{-rT}} \tag{2.2}$$

where, C is the above ground carbon stock in rubber plantations (Mg C ha^{-1}), C_{max} is the maximum above ground carbon stock in rubber plantations (Mg C ha^{-1}), T is the stand age of the rubber trees (years), e is the exponential function, m and r are the constants.

The best-fit model was used for calculation of C_{ta}, at time corresponding to median rotation length value of both lowland and highland rubber plantations (Supplementary material Figure S2.1 a). We regarded the sampled maximum stand age of lowland and highland rubber as their maximum rotation length. Thus, the median rotation length will be half of this maximum rotation length, referring to 17.5-year and 12.5-year, respectively.

2.2.2.4.2 Tree-based system

In NRWNNR, natural forest, monoculture plantations such as banana plantations and tea gardens were classified as belonging to tree-based systems. We assumed that the natural forest has a fairly constant carbon stock and age of 100 years, which is based on interviews with local farmers and consultations with NRWNNR officers. The surveyed banana and tea plantations were both included establishment and production phase. According to Zhang et al. (2013), the establishment time for tea garden is 25 years, and after that carbon stock will keep stable and acting as production phase. In our study site, the local farmers cultivated banana with maximum three years rotation length (two years in establishment phase and after that has one year production phase) to fulfill the optimum production, which is different from traditional planting of banana plantation with more than 20 years rotation. The carbon accumulation rate was calculated as:

$$I_c = C_{max} / T_r \quad (2.3)$$

where I_c = carbon accumulation rate per year (Mg C ha^{-1} year^{-1}), C_{max} = maximum carbon sequestered in tree-based system (Mg C ha^{-1}), T_r = rotation time (years).

Fruit tree plantations keep producing fruits after reaching maximum carbon stock level. Therefore, the C_{ta} for fruit tree plantations is the weighted average of establishment phase (C_{ta1}) and production phase (C_{ta2}), as shown in Supplementary material Figure S2.1 b. We assume that the carbon stock of production phase is equal to C_{max}, with the time-averaged carbon stock for the establishment phase (C_{ta1}) was calculated as shown in equations 4 and 5 (Palm et al., 2000; Hariah et al., 2011):

$$C_{ta1} = T_{max} * I_c / 2 \quad (2.4)$$

$$C_{ta} = [(C_{ta1} * T_{max}) + (C_{ta2} * (T_r - T_{max}))] / T_r \quad (2.5)$$

where T_{max} is the time to reach maximum carbon stock (years).

2.2.2.4.3 Crop-fallow system

The carbon accumulation rate during the fallow phase of a crop fallow system (Supplementary material Figure S2.1 c) is described in equations 6 and 7:

$$I_c = C_{max}/T_f \quad (2.6)$$

with T_f is time in fallow phase (years). The time-averaged carbon stock of crop-fallow system is:

$$C_{ta} = (I_c * T_f)/2 \quad (2.7)$$

Maize cropping, as well as bush and grassland were classified as crop-fallow system. The I_c of maize monoculture in our study case was estimated by the same manner using the cropping time (around 0.3 year) instead of fallow time. Half of maximum C stock (6 Mg C ha^{-1}) was regarded as the C_{ta} during its growing time (Hairiah et al., 2011).

2.2.2.5 Landscape level carbon stock assessment

In the present study, based on data availability, a 1989 land-use/land-cover (LULC) map was digitized from the first monitoring report of NRWNNR (Tao,1989), which represents historic land use conditions before the official authorization of the nature reserve in 1991. The 2007 LULC map was obtained from LILAC project (http://lilac.uni-hohenheim.de/en/index.php), and the 2012 LULC map was obtained from SURUMER project (https://surumer.uni-hohenheim.de/), the detailed information of these LULC maps please refer to Supplementary material Table S2.1. In order to integrate ground truth data with satellite data, the consistency of land use categorization should be checked. In this way, we re-sampled LULC maps into 30 m and re-defined the land use systems into forests, rubber plantations, agricultural crops, bush and grassland, as well as other land use types (including settlements, roads, lakes and open soil). By using a Digital Elevation Model (DEM) from an ASTER 30 m satellite dataset, we further classified forest into lowland forest and highland forest, and rubber plantations into lowland rubber and highland rubber by using 800 m a.s.l. as a cut-off line. By multiplying each land use type’s area with its C_{ta}, carbon stock respective maps could be derived for 1989, 2007 and 2012. If the difference between time series showed net carbon gain, then it indicated a carbon sequestration potential of the recent land use type compared to the previous land use and, conversely, carbon loss occurred if the more recent land use type had caused net carbon emissions compared to the previous land use. The sum of all land use types' carbon stock differences between the time series display the net carbon sequestration or net carbon emission trend within the different landscapes of NRWNNR. All described processes were carried out by using ArcGIS 9.3 software, details could refer to Supplementary material Figure S2.2. .

2.2.2.6 Rubber plantation related land use conversions and their impact on carbon emission/sequestration

After preparing carbon emission/sequestration maps for time periods of 1989-2007, 2007-2012 and 1989-2012, the nature reserve was divided by its functional zones, referring to core, buffer and experimental zone. Within each zone, a land use change matrix was prepared and using GIS technique, the difference between previous and current C_{ta} values of each land use type were multiplied by changed land area. If this value turned out to be positive, then it indicated carbon sequestration, otherwise it represented a carbon emission effect within that functional zone. The hotspots of land use change were identified, and corresponding carbon emission or sequestration values were calculated within each functional zone. The area change percentage was derived from the changed land use area divided by its corresponding functional zone's area.

2.2.2.7 Sensitivity analysis

Most relevant studies applying C_{ta} for landscape level carbon emission/sequestration assessments, were missing the uncertainty and sensitivity analysis part, which was very important to understand potential source of error. We manipulated with C_{ta} and estimated the effect of these changes on total C emission/sequestration by applying the coefficient of sensitivity (*CS*), this was calculated based on the standard economic concept of elasticity (Stigler, 1987). Previous studies adopted 50% modification of original value for testing corresponding changes of *CS* (Hu et al.,2008), We follow a rather conservative approach in the present study, the calculated C_{ta} values of major land use systems including lowland forest, highland forest, lowland rubber, highland rubber, agricultural crops, bush and grassland were adjusted by 20%. The corresponding *CS* values were derived as shown in equation 2.8:

$$CS = \frac{(TotC_j - TotC_i)/TotC_i}{(Cta_{jk} - Cta_{ik})/Cta_{ik}} \qquad (2.8)$$

Where $Tot\ C_j$ is the estimated total carbon emission or sequestration value of NRWNNR, C_{ta} is the time-averaged above ground carbon stock value, *i* and *j* stands for initial and adjusted values, *k* represents the land use types.

If the *CS* value is greater than one, then we could assume that the estimated total carbon emission or sequestration of NRWNNR is elastic with respect to the adjusted C_{ta}, but if the *CS* value is less than one, then the estimated total carbon emission or sequestration value is regarded as inelastic. The elasticity here stands for the decreasing robustness or increasing of uncertainty of whole landscape carbon emission or sequestration assessment, with the adjustment of land use systems C_{ta}.

2.3 Results

2.3.1 Current carbon stocks of land use systems

Carbon stored in above ground tree parts and topsoil accounted for the majority of all carbon in the different pools measured (>84%) (Table 2.3). Root carbon accounted for a lesser proportion (<15%) and varied according to land use type. Necromass and understory carbon stocks were smallest among all carbon pools (<4%). Lowland forests had the highest mean carbon stocks at 183 Mg C ha^{-1}. The category of lowland forest included tropical rainforest, tropical seasonal rainforest and mingled forest with bamboo. Tropical rainforest contained the most carbon at 289 Mg C ha^{-1} of tree aboveground biomass (AGB) carbon, 38% higher than tropical seasonal rainforest.

Mingled forest with bamboo had relatively shorter succession length (60 years) and lower averaged tree AGB (37 Mg C ha^{-1}) than other lowland forest types. This reflects its simplified plant structure as compared with a primary tropical rainforest. Highland forest had the second highest mean carbon stocks, at 140 Mg C ha^{-1}. The types of highland forest consist of broadleaved deciduous forest, seasonal evergreen broadleaved forest and montane rainforest. The broad-leaved deciduous forest contained 203 Mg C ha^{-1} of tree AGB, followed by montane rainforest (149 Mg C ha^{-1}) and seasonal evergreen broadleaved forest (103 Mg C ha^{-1}). Lowland rubber plantations had on average 56 Mg C ha^{-1} of tree AGB, which was lower than the averaged tree AGB of lowland and highland forest. However, lowland rubber plantations had much higher AGB than that of highland rubber plantations (22 Mg C ha^{-1}) and other land use types, such as agricultural crops (12 Mg C ha^{-1}), or bush and grassland (8 Mg C ha^{-1}). The dominant rubber clone types in NRWNNR were GT1 and RRIM600, which occupied more than 80% in lowland area, while there still other new clone types available and distributed in highland regions (774, 772, etc.). The planting density of lowland plantations ranged from 360-860 tree ha^{-1}, and highland rubber plantations has 520-900 tree ha^{-1}. The soil carbon stock under the natural forest, bush and grassland was larger than topsoil carbon stocks in cultivated plantations and under agricultural crops.

2.3.2 Time-averaged carbon stock of land use systems

The above-ground carbon stocks for lowland and highland rubber plantations were plotted according to the age of the stand (Figure 2.4). The predicted maximum above ground carbon density of lowland rubber plantations was 148 Mg C ha^{-1} at a rotation length of 35 years, while that of highland rubber plantations was 50 Mg C ha^{-1} at a rotation length of 25 years. Based on equations (2.2) - (2.7) (Section 2.2.4), the above ground C_{ta} for other land use types were derived and displayed in Table 2.4. Natural forest showed a higher above ground C_{ta} value than cultivated plantations and agricultural crops. Moreover, bush and grassland displayed the lowest value

Table 2.3 Current carbon stocks in different land use types in NRWNNR, Xishuangbanna, China, with arithmetic means referring to Mg C ha^{-1} ± S.E.

		Current C stock (Mg C ha^{-1} ± S.E)							
Land use/land cover	**Number of Plots**	**Tree aboveground**	**Understory**	**Necromass**	**Total above ground** [a]	**Root**	**Soil (0-30 cm)**	**Total plot**	**Sampling maximum rotation length**[b]
Lowland forest (< 800 m) [c]	8	183 ± 72	0.38 ± 0.08	6 ± 1	189 ± 72	41 ± 18	79 ± 6	309 ± 91	100
Tropical seasonal rainforest	4	209 ± 85	0.39 ± 0.15	7 ± 2	217 ± 85	47 ± 21	75 ± 5	338 ± 101	100
Tropical rainforest	2	289	0.34	6	295	68	92	455	100
Mingled forest with bamboo	2	37	0.42	4	42	4	72	117	60
Highland forest (> 800 m)	8	140 ± 20	0.34 ± 0.07	5 ± 2	145 ± 19	29 ± 4	82 ± 3	256 ± 38	100
Seasonal evergreen broadleaved forest	4	103 ± 11	0.32 ± 0.10	8 ± 3	111 ± 10	21 ± 2	75 ± 1	207 ± 46	100
Broad-leaved deciduous forest	2	203	0.56	2	206	47	85	338	100
Montane rainforest	2	149	0.17	3	152	25	88	265	100
Rubber plantation									
Lowland rubber (< 800 m)	11	56 ± 11	0.15 ± 0.02	2.11 ± 0.28	58 ± 11	10 ± 1	56 ± 3	124 ± 14	35
Highland rubber (> 800 m)	14	22 ± 5	0.20 ± 0.06	1.76 ± 0.33	24 ± 5	5 ± 1	62 ± 3	91 ± 5	25
Agricultural crops	7	12 ± 3	0.04 ± 0.01	0.79 ± 0.17	13 ± 3	3 ± 1	68 ± 13	84 ± 15	40
Maize	3	6 ± 2	0.05 ± 0.02	0.50 ± 0.01	6 ± 2	1.67 ± 0.51	50 ± 4	58 ± 6	0.3
Banana	2	13	0.02	1	15	3	56	73	3
Tea	2	21	0.04	0.70	21	6	73	101	40
Bush and grassland	3	8 ± 2	0.22 ± 0.05	0.3 ± 0.14	8 ± 2	14 ± 3	73 ± 13	96 ± 12	100

Note：[a] total above ground carbon stocks included carbon stocks from tree above ground, understory vegetation and necromass; [b] This stands for the oldest stand age of this land use type during field sampling, this information was obtained from local farmers and also confirmed by nature reserve's officers. The mingled forest with bamboo belongs to secondary forest, thus 60-year was the longest succession stage during forest sampling, while other forest types were approximately 100-year old; [c] This row refers to the averaged mean and standard error of the whole category, i.e. the value of tree above ground carbon stock was calculated from 8 plots of tropical seasonal rainforest, tropical rainforest and mingled forest with bamboo. The aggregation of ground surveyed land use types was performed to enable linking with classified land use types from satellite data.

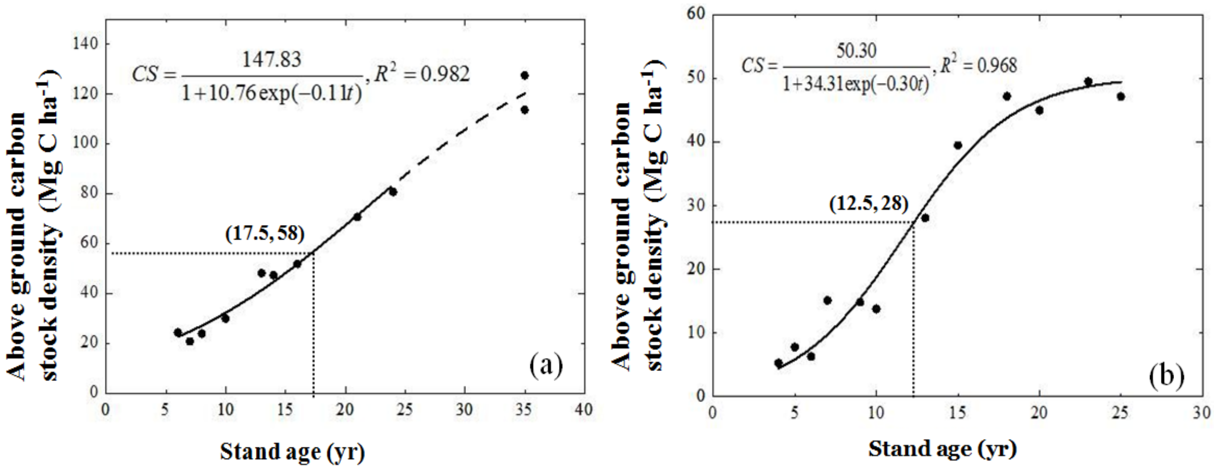

Figure 2.4. Aboveground carbon stock dynamics described by logistic equation for (a) lowland and (b) highland rubber plantations in NRWNNR, Xishuangbanna, China, with $P < 0.01$. The dashed line in (a) represents rubber plantations with stand age older than 25years. Time-averaged above ground carbon stock was estimated at median time 17.5 and 12.5 years for lowland and highland plantations respectively.

among all land use types considered. Lowland rubber and highland rubber had C_{ta} of 58 Mg C ha^{-1} and 28 Mg C ha^{-1}, respectively.

2.3.3 Impact of rubber cultivation on local time-averaged carbon emission/sequestration

The changes of each land use type area are shown in Table 2.5, with corresponding carbon emission/sequestration and annual rates referring to 1989, 2007 and 2012, respectively. The area of lowland forest reduced by 20.2 % from 1989 to 2007, and further decreased by 8.5 % from 2007 to 2012. In contrast, highland forest increased by 32.3% from 1989 to 2007, and by 4.6% during 2007 to 2012, mainly as a result from reforestation activities and less human disturbances in the nature reserve. Lowland rubber plantations showed an annual expansion rate of 56 ha yr^{-1} during 1989-2007, but the area decreased by 10.4% during 2007-2012, due to conversion to other land use types, such as banana plantations, as most of lowland rubber plantations had already reached their maximum rotation length. Highland rubber plantations continued to increase in the considered time frame with an average expansion rate of 71.5 ha yr^{-1}. Besides, agricultural crop area and other land use types' area increased by 49% and 297% during 1989-2012, while bush and grassland area decreased by 84.5% during the same time period. Following the LULC dynamics during 1989-2012, NRWNNR as a whole showed a net carbon gain (time-averaged) of 0.565 Tg C and 0.079 Tg C during 1989-2007 and 2007-2012, respectively. Taking the whole evaluated time span into consideration (1989-2012), the contribution of carbon emission/ sequestration per land use type indicated that highland forest areas

Table 2.4. Basic parameters for calculating time-averaged carbon stock of dominant land use cover types.

Land use/land cover	Calculation Equation/ method	T_r (year)	T_{max}	C_{max} (Mg C ha^{-1})	C_{ta1}	C_{ta2}	C_{ta}	I_c (Mg C ha^{-1} yr $^{-1}$)
Lowland forest (<800m)							**185[a]**	**1.94**
Tropical seasonal rainforest	$C_{max} = C_{ta}$	100	100	217	217	0	217	2.17
Tropical rainforest	$C_{max} = C_{ta}$	100	100	295	295	0	295	2.95
Mingled forest with bamboo	$C_{max} = C_{ta}$	60	60	42	42	0	42	0.70
Highland forest (>800m)							**156**	**1.56**
Seasonal evergreen broadleaved forest	$C_{max} = C_{ta}$	100	100	111	111	0	111	1.11
Broad-leaved deciduous forest	$C_{max} = C_{ta}$	100	100	206	206	0	206	2.06
Montane rainforest	$C_{max} = C_{ta}$	100	100	152	152	0	152	1.52
Rubber plantation								
Lowland rubber (<800m)	Equation (2.2)	35	35	148	58	0[b]	**58**	**4.23**
Highland rubber (>800m)	Equation (2.2)	25	25	50	28	0	**28**	**2.00**
Agricultural crops							**9**	**9.45**
Maize	Equation (2.6-2.7)	0.3	0.3	6	6	0	3	20
Banana	Equation (2.3-2.5)	3	2	15	8	15	10	7.50
Tea	Equation (2.3-2.5)	40	25	21	11	21	15	0.84
Bush and grassland	Equation (2.6-2.7)	100	100	8	8	0	**4**	**0.08**

Note: rotation time (T_r), the time to reach its maximum production (T_{max}) , maximum C stock (C_{max}), time-averaged C stock for establishing phase (C_{ta1}), time-averaged C stock for production phase (C_{ta2}), time-averaged C stock over entire rotation (C_{ta}), annual aboveground carbon accumulation rate (I_c)

[a] derived from the averaged value of C_{ta} of lowland forest category, similar for I_c

[b] latex production was not considered in production phase (C_{ta2}), as this information was not available in all sampled plots. Rubber plantations normally show continuous increasing trend of carbon stock with the longer rotation length (Figure 2.3 a, b). Here they didn't have a real "establishment phase" like fruit trees, although the tapping starting age (7 years) could be an indicator for coming into mature stage/production stage, the biomass still kept increasing rather than arriving a maximum condition.

have a great potential for carbon storage, with a carbon sequestration rate of 1.16 Mg C ha^{-1} yr^{-1}, while decreasing lowland forest area led to a carbon emission rate of 0.23 Mg C ha^{-1} yr^{-1} once converted to other land use types.

The top six land use change trajectories are displayed in Figure 2.5 (a, b, c), together with their carbon gain/loss (Figure 2.5 d, e, f) distributions, the detailed land use conversion in different functional zones in NRWNNR and its corresponding carbon emission/sequestration was reported in Supplementary material Table S2.2. During 1989-2012, carbon emissions larger than 0.1 Tg C mainly resulted from highland forest conversion to highland rubber plantations (carbon loss 128 Mg C ha^{-1}), and highland forest transition into agricultural crops (carbon loss 147 Mg C ha^{-1}). The establishment of lowland rubber plantations in former forest areas (carbon loss 127 Mg C ha^{-1}) caused carbon emissions between 0.05 Tg C and 0.1 Tg C. Estimations of carbon sequestration larger than 0.3 Tg C mainly derived from newly regenerated highland forest in former bush and grassland areas (carbon gain 181 Mg C ha^{-1}), located in the northeastern and southwestern parts of NWNNR. Most of the forest-to-rubber conversions occurred in the buffer and experimental zones, especially at high elevation ranges, while no rubber relevant land use conversions were found in the core zone. Rubber expansion into forest area caused a larger effect in the experimental zone compared to the buffer zone, with a carbon emission value of 0.057 Tg C and 0.095 Tg C in lowland and highland, respectively. The artificial reforestation activities launched by local forest officers in experimental and buffer zone served as an effective way to cope with carbon emission from rubber intensification, meanwhile, the natural regeneration in core zone also contributed to carbon sequestration.

2.3.4 Sensitivity analysis of variation in time-averaged carbon stocks on landscape carbon emission/sequestration

The effect of adjusted time-averaged above-ground carbon stock value on landscape carbon emission/sequestration in 1989 and 2012 is shown in Table 2.6. The Coefficient of Sensitivity (*CS*) value of the computed analysis was less than one in all considered cases, which implies that our estimates were robust and uncertainty was within acceptable level. We found the adjustment of above ground C_{ta} of highland

Table 2.5 Landscape based carbon emission (negative values) or sequestration (positive values), and emission or sequestration rate related to land-use change in NRWNNR, Xishuangbanna, China, from 1989 to 2012. In current study we assume carbon stock for other land use types is zero.

Land use types	**Area (ha)**			**C emission/ sequestration (Tg)**						**C emission/sequestration rate (Mg C ha^{-1} yr^{-1})**		
	1989	**2007**	**2012**	**C1989-2007 [a]**	**CC_k[b] (%)**	**C2007-2012**	**CC_k (%)**	**C1989-2012**	**CC_k (%)**	**R1989-2007 [c]**	**R2007-2012**	**R1989-2012**
Lowland forest	2819	2249	2057	-0.106	-4.32	-0.035	-0.01	-0.141	-5.78	-0.22	-0.27	-0.23
Highland forest	11809	15634	16355	0.597	24.47	0.112	0.04	0.709	29.08	1.25	0.85	1.16
Lowland rubber	274	1282	1149	0.058	2.40	-0.007	0	0.051	2.08	0.12	-0.06	0.08
Highland rubber	64	1240	1709	0.033	1.35	0.013	0	0.046	1.89	0.07	0.10	0.08
Agricultural crops	2232	3154	3325	0.008	0.34	0.002	0	0.010	0.40	0.02	0.01	0.02
Bush and grassland	9360	2876	1451	-0.025	-1.06	-0.006	0	-0.031	-1.30	-0.05	-0.04	-0.05
Other land use types	100	185	397	0 [d]	0	0		0	0	0	0	0
Sum	26658[e]	26620	26443	0.565		0.079		0.644		1.181	0.589	1.052

[a] C1989-2007 stands for carbon emission/sequestration during 1989 - 2007

[b] CC_k stands for relative change in carbon emission/sequestration, e.g. relative change of carbon emission/sequestration from 1989 to 2007 : $CC_k = (C_{2007} - C_{1989}) / \sum C_{1989}$

[c] R1989- 2007 stands for carbon emission or sequestration rate during 1989 – 2007

[d] Here we assume other land use types (including settlements and water bodies) carbon stock value as zero.

[e] Difference of area of NRWNNR in 1989, 2007 and 1989 due to resampling of LULC maps into a 30 x 30 m resolution, with the averaged area 26574 ha adopted for C emission/sequestration rate calculations.

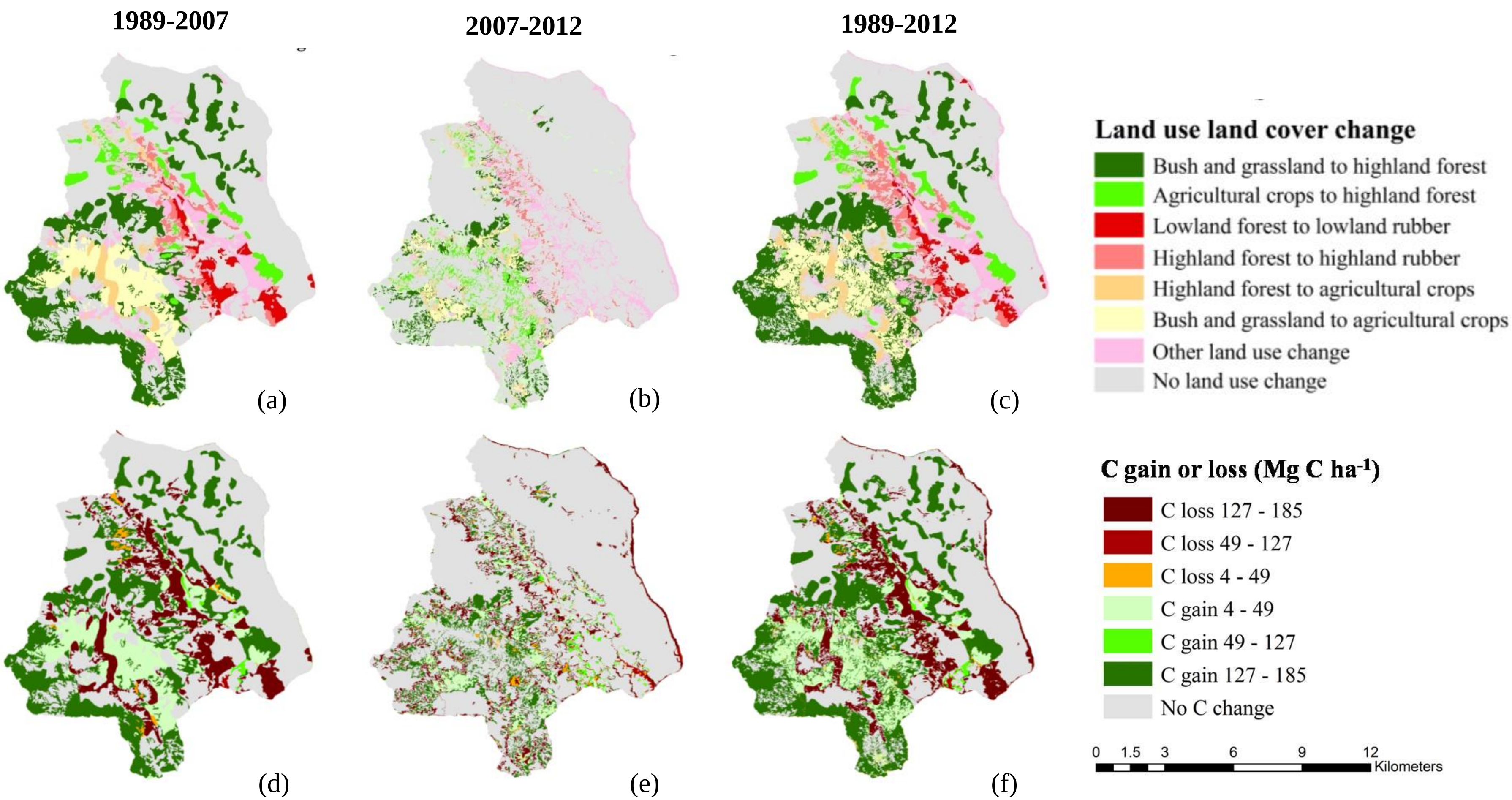

Figure 2.5. Land-use changes (a, b, c) and corresponding carbon gain/loss (Mg C ha^{-1}) (d, e, f) in NRWNNR, Xishuangbanna, China, during the periods of 1989-2007, 2007-2012 and 1989-2012

forest (increase or decrease 20%) showed the highest change magnitude in total carbon sequestration (0.502 Tg C - 0.785 Tg C), referring to the crucial role of highland forests in determining carbon gain or loss in our case study. From 1989 to 2012, the *CS* values of lowland and highland forest revealed larger changes than other land use types, the former decreased from 0.21 to 0.12, while the latter increased from 0.75 to 0.83. Other land use types' *CS* value showed changes lower than 0.02.

Table 2.6 Landscape carbon sequestration/emission values and coefficients of sensitivity (*CS*) after adjusting for time-averaged above ground carbon stock (C_{ta}).

Change in time averaged carbon stock (*AdjC_{ta}*)	***AdjTotC* (Mg C) value**[a]		**Effect of changing C_{ta} from original**			
	***AdjTotC* 1989**[b]	***AdjTotC* 2012**	**1989 (%)** [c]	**CS_{1989}**	**2012 (%)**	**CS_{2012}**
Lowland forest						
+ 20%	2.543	3.158	4.26	0.21	2.47	0.12
– 20%	2.335	3.006	-4.26	-0.21	-2.47	-0.12
Highland forest						
+ 20%	2.807	3.592	15.09	0.75	16.55	0.83
– 20%	2.070	2.572	-15.13	-0.76	-16.55	-0.83
Lowland rubber						
+ 20%	2.442	3.095	0.12	0.01	0.42	0.02
– 20%	2.436	3.069	-0.12	-0.01	-0.42	-0.02
Highland rubber						
+ 20%	2.439	3.092	0	0	0.32	0.02
– 20%	2.439	3.073	0	0	-0.29	-0.01
Agricultural crops						
+ 20%	2.443	3.088	0.16	0.01	0.19	0.01
– 20%	2.435	3.076	-0.16	-0.01	-0.19	-0.01
Bush and grassland						
+20%	2.446	3.083	0.29	0.01	0.03	0
– 20%	2.431	3.081	-0.33	-0.02	-0.03	0

[a] Total carbon sequestration value of NRWNNR before adjustment (*TotC*) were 2.439 Tg C and 3.082 Tg C in 1989 and 2012 respectively.
[b] *AdjTotC*1989 stands for total carbon emission or sequestration value after adjusting C_{ta} in 1989.

2.4 Discussion

2.4.1 Rotation length, elevation range and site conditions determine rubber plantation long-term carbon stock evaluation

In order to make different land use systems comparable we used 'time-averaged carbon stock' (C_{ta}) as a base unit, which decreases uncertainties in assessing carbon stocks of crops or plantations with different rotation lengths. The inclusion of different life cycles of various land use types thus provides a more consistent monitoring of the changes of carbon stocks throughout a whole landscape, and avoids over- or under-estimation of carbon stocks when assessing plot-level data during different succession stages. Based on the results of the present study, we would recommend taking into account rotation length, elevation range and site condition of rubber plantations in the C_{ta} calculation, for both agro-forestry rubber systems and monoculture rubber systems. Studies carried out for various agro-forestry rubber systems (Palm et al., 2000; Palm et al., 2005) obtained differences in C stocks for permanent rubber agro-forest systems (49.4-129 Mg C ha^{-1}) and rotational rubber agro-forestry systems (28.9-75.2 Mg C ha^{-1}) with mean values of 89.2 Mg C ha^{-1} and 46.2 Mg C ha^{-1} respectively. Only a few studies assessed rubber monoculture (Widayati et al., 2011; Lusiana, 2013), but without consideration of elevation effects on C stocks, which can strongly affect the landscape level assessment in mountainous landscapes in general. Our study was able to reveal significant differences between lowland and highland rubber plantations in monoculture systems, which is important for long-term carbons stock evaluations. Thus, a separate application of elevation-differentiated C_{ta} estimates could decrease a potential overestimation of C stocks when upscaling to landscape level. For example, if the C_{ta} value of lowland rubber plantation was used to represent highland rubber plantation, the carbon sequestration value in NRWNNR for 1989, 2007 and 2012 would be 2.78 Tg, 3.46 Tg and 3.56 Tg respectively, which would refer to an approximately 15% over-estimation of the potential actual carbon stock. In our study, a lowland rubber plantation comprised about a 2-times larger carbon stock if compared with highland rubber. This difference in C_{ta} estimates might be lower, if a longer rotation time for higher elevations would be considered due to the slower growth. A few studies explored stand age influence on rubber plantations' carbon stock in tropical regions of South East Asia (Wauters et al., 2008; Tang et al., 2009; Song and Zhang, 2010; Petsri et al., 2013; Song et al., 2014), and established different growth regressions. However, none of them calculated C_{ta}. In order to make a comparison between different published results possible we calculated the respective C_{ta} (using a 25-year rotation length) based on their published growth regressions (Figure 2.6, refer to Supplementary material Table S2.3 for detail). The result revealed a consistent decrease of C_{ta} with increase in elevation across a range of sites in the tropical rainforest biome. However, rubber plantations located in the savanna biome displayed lower C_{ta} than those in a corresponding tropical rainforest biome in regions lower than 500 m (Ghana, Thailand and Brasil). This probably reflected differences in tree development under two contrasting biome site conditions. Additionally, the different clone types planted in various locations may have different tree architectures. Therefore, variations in tree height and circumference growth patterns would affect calculated biomass and C_{ta}, which would imply the need for site or clone specific allometric equations (Dey et al., 1996; Wauters et al., 2008). Our results that C_{ta} of rubber plantations at higher elevation was substantially lower than at lower elevations in Xishuangbanna, are consistent with those obtained by Song and Zhang (2010). In some circumstances, the difference of C_{ta} in lowland of Xishuangbanna and highland of NRWNNR was not obvious, e.g. Tang et al. (2009) and Song et al. (2014), attributed to the compensation of low individual tree biomass by dense cultivation of rubber trees (520-900 tree ha^{-1}) in highland of NRWNNR. Yi et al. (2014b) reported the state-owned rubber plantations were dominant in lowland area of Xishuangbanna, with a standard planting density of 495 tree ha^{-1}, while the smallholder-owned rubber plantations were dominant in high elevation areas of Xishuangbanna with much higher cultivated tree density (580-850 tree ha^{-1}). Therefore, in order to increase landscape level carbon accounting accuracy, it is advisable to evaluate rubber plantations with specifications of sampling stand age, elevation range and site conditions (e.g. planting density, clone type) to allow a more reliable comparison with other land use types sampled during the same assessment period.

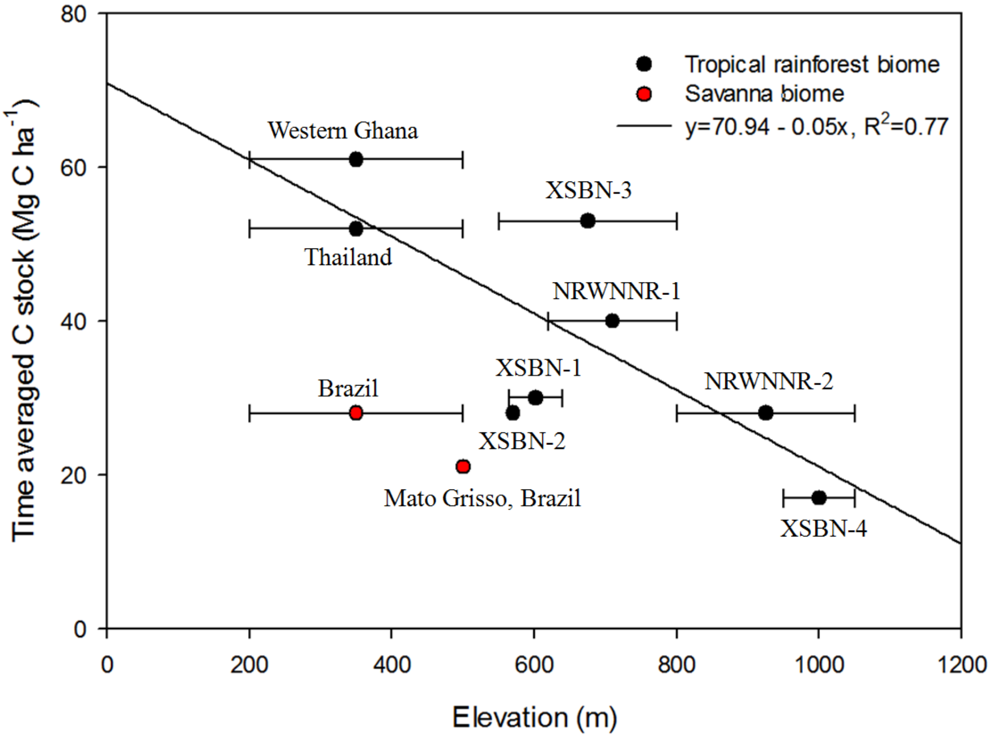

Figure 2.6. Time-averaged above ground carbon stock estimated from logistic growth function for rubber plantations (Wauters et al., 2008; Tang et al., 2009; Song and Zhang, 2010; Petsri et al., 2013; Song et al., 2014 and current study). The sites name and specific time-averaged carbon stock values could refer to Appendix's "Location" and "*Est* C_{ta}". Black line represents the simulated relationship between time-averaged carbon stock (y, Mg C ha^{-1}) and elevation (x, m) for tropical rainforest biome.

2.4.2 The importance of forest above ground carbon stock assessment

We applied more detailed forest type classification schemes and clearer separation of elevation effects than is commonly applied. Studies often poorly characterize the relationship between elevation and different forest types carbon stocks (Ensslin et al., 2015). The comparison of our results with other studies conducted in Xishuangbanna, confirmed the reliability of our ground survey. We found that natural forests still comprise the major carbon pools in NRWNNR. For instance, tropical seasonal rainforest had an AGB mean value of 209 Mg C ha^{-1}, which is within reported values' range (128 -294 Mg C ha^{-1}) (Feng et al., 1998; Zheng et al., 2000; Lu et al., 2006; Liu et al., 2006; Lü et al., 2007); while montane rainforest had a mean value of 149 Mg C ha^{-1}, i.e. 23-39% lower than published results (193 and 246 Mg C ha^{-1}) (Huang et al., 1991; Li et al., 1996). Above ground biomass carbon stock in tropical rainforest (289 Mg ha^{-1}) was higher than other published data in Xishuangbanna (Dang et al., 1997; Bao et al., 2008). The reason for the discrepancy in the latter case could be different DBH ranges and succession stage of forest in compared data sets which make sites-to-sites comparison challenging. Our estimates for seasonal evergreen broad-leaved forest (103 Mg C ha^{-1}) and mingled forest with bamboo (37 Mg C ha^{-1}) were similar to results of Li et al. (2008) and Guo et al. (1987) with carbon stock values of 105 Mg C ha^{-1}and 30 Mg C ha^{-1}, respectively. Moreover, the current study represented 6 major forest types located in 2 elevation ranges. They displayed different AGB at various elevation levels, which call for more attention to identify elevation effects on forest AGB distribution in future studies.

The current assumption that the oldest forest stands sampled in the field surveys could represent a climax stage of this forest type showed its limitation. Indeed, in NRWNNR the emerging young secondary forest was less than 15 years old, while the primary old-growth forest already reached an age of up to 200 years (Mo et al., 2011). If the sampled maximum carbon stock was taken as C_{ta} and put into account, subsequently an over-or under-estimation was possible, which depended on the forest distribution area with various succession stages. In our study, detailed forest inventory information was not accessible, thus uncertainty analysis relevant to forest sampling could not be carried out with forest patches and age information. More information on forest age could help in estimation of C_{ta} and this task should be also considered in future studies. The sensitivity analysis further revealed that natural forest exhibited a higher coefficient of sensitivity than other land use types due to its relatively larger carbon stock and distribution area compared to other land use types. Therefore, the reliability of survey data of the above ground carbon stock for natural forest highly influences whole landscape carbon emission or sequestration changes.

2.4.3 Limitations of- and implications from current carbon accounting approach

All main plant and soil carbon pools were surveyed in our study, however, only the total above ground biomass (AGB) was used for C_{ta} estimation. Thus, our approach was different from previous studies, which also included soil organic carbon (SOC) and below ground biomass (BGB) into accounting (Van Noordwijk et al., 2002; Hairiah et al., 2011). The underestimation of total ecosystem carbon stocks due to excluding of SOC and BGB from C_{ta}, is evident. This further influences sensitivity analysis and affect results interpretation. However, we hold a conservative attitude when taking into account the uncertainties from SOC and BGB sampling. For instance, using SOC sampled from surface soil (30cm) underestimates the total soil carbon stock. Extrapolation of surface SOC data to whole soil profile SOC stock would cause a large uncertainty. If the sampled rubber plantation were established on soils with different initial SOC depending on previous land use types, it resulted in estimation bias for total C stock (Blagodatsky et al., 2016). Recent studies also confirmed the decreasing SOC by average 19% down from forest-to-rubber plantation conversion over 46 years of rotation length (de Blécourt et al., 2013). However, the land cover type preceding rubber is not always known, so that SOC change cannot be reliably estimated if detailed land use history is not available. Regarding to BGB sampling, the paucity of available dataset published for BGB of different land use types still constrain its further application in carbon accounting. In addition, various root shoot ratio/allometric equations, sampling protocol, or site condition greatly influence the estimated value of BGB (Yuen et al., 2013; Yuen et al., 2016). Therefore, we advise to consider AGB only for C_{ta} estimation in study regions encountered obvious effect from land-use change, e.g. conversion to rubber. Reliable comparison of C_{ta} among different studies can be achieved if the same components of carbon pools are used to calculate C_{ta}.

2.4.4 Land use management in mosaic agricultural landscape in nature reserves

In the current context, NRWNNR was regarded as biosphere reserve, which follows the concept of the United Nations Educational, Scientific and Cultural Organization’s (UNESCO) Man and the Biosphere Program (MAB), consisting of a core zone of strictly conservation, a buffer zone for limited human activities and an experimental zone mainly to fulfill human production needs (UNESCO, 1996). There were three principles guiding the establishment of NRWNNR: the unchanged forest land tenure, a stable administrative boundary and the permission of local residents to live inside the nature reserve (Tao, 1989). This is a unique forest management and conservation strategy which calls for an integrated management approach between humans and the natural environment, and thus to meet the balance of local community development and forest resource protection. Before the official establishment of the nature reserve, forests were easily influenced by human activities, such as traditional slash and burn activities for shifting land cultivation, or exchanging forest land into cash crop plantations, such as rubber (Tao. 1989). In NRWNNR, rubber plantation area increased more than 10 times during 1989 to 2012, with rubber relevant land-use change trajectories occurring only in buffer and experimental zones, while important habitats and forest resources of endangered flora and fauna in the core zone were not influenced by rubber expansion. The striking results showed high carbon emissions due to conversion of highland forest to rubber plantation; and conversely carbon sequestration was achieved by converting lower C_{ta} land use types (such as agricultural crops, bush and grassland) to higher C_{ta} land use types (such as rubber plantations and natural forest). These findings are consistent with observations by Hashimotio et al. (2000) and Yi et al. (2014a). Indeed, planting rubber plantations could increase landscape level carbon storage as shown in several studies (e.g. Fox et al., 2014), providing that the previous land use is of lower carbon stock value. Rubber plantations replacing traditional shifting cultivation below 1500 m a.s.l. satisfy both natural rubber demand and increase of ecosystem carbon stock (Li et al., 2008).

However, different carbon sequestration pathways represent different roles of the experimental and buffer-functional zones. In lowland areas, there was negligible arable land converted to forest in the experimental zone when compared with the buffer zone. This is a reasonable outcome as the main function of the experimental zone is to meet the requirements of local agricultural production and maintain food security. Beyond issues of carbon management in such mosaic agricultural landscapes, there are often concerns for its landscape connectivity and species richness which might potentially be threatened by loss of forest area from land use conversion (Xu, 2011; Li et al., 2007). Jantz et al. (2014) pointed out the need of identifying 'carbon corridors' in both protected and un-protected areas which could serve as an effective approach for preserving forest carbon stocks through land use conversion, as well as achieving habitat connectivity and climate change mitigation, and identifying needs for future carbon management studies.

2.5 Conclusions

We recommend the time-averaged carbon stock (C_{ta}) concept as a useful tool to cope with the uncertainties arising from evaluation of various land use systems with different rotation lengths. In regions with large land-use changes, the AGB was advisable for calculation of C_{ta}, however the under-estimation of total C stocks resulted from excluding BGB and SOC should be also considered. In order to reliably assess the carbon storage potential of rubber plantations, we emphasize the importance of rotation length, elevation gradient, and site condition's effects (e.g. planting density, clone type) when calculating C_{ta}, for both agro-forestry rubber systems and mono-cultural rubber systems in tropical regions of South East Asia. The sensitivity test showed forest carbon stocks played an important role in landscape carbon assessment. Their evaluation can be substantially improved by application of detailed forest type classification schemes and differentiating elevation effects. The current study found that lowland and highland rubber plantations secured a larger carbon sequestration potential than non-forest land use types (agricultural crops, bush and grassland), but they had a much lower carbon sequestration potential than that of natural forests. Answering the posed research questions, we reveal that: 1) rubber plantations cannot compensate carbon losses due to deforestation in NRWNNR; 2) rubber replacing former bush and grasslands or agricultural land increased above-ground carbon by 19 - 54 Mg C ha^{-1}; 3) reforestation based on a functional zoning strategy in nature reserves could help in mitigating C losses caused by expansion of rubber plantations or other land uses. The latter solution helps to meet the balance of local community development and forest resource protection in the long term.

2.6 Supplement

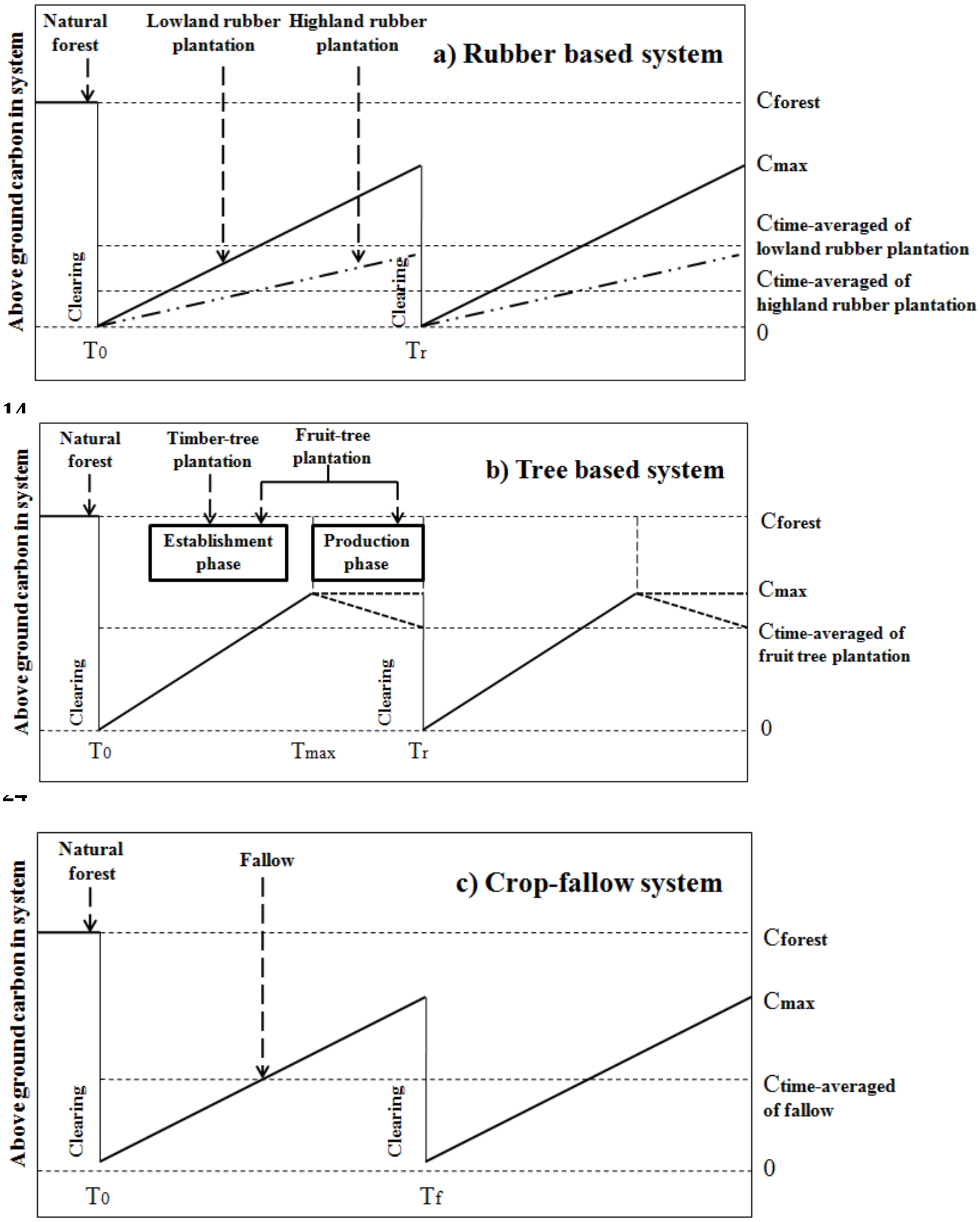

Figure S2.1. Scheme of the temporal changes in carbon stock for calculating time-averaged carbon stock after forest clearing and establishment of (a) rubber based system, (b) tree based system, (c) crop-fallow system. Carbon stored in natural forest (C_{forest}), maximum carbon stored during rotation length (C_{max}), time-averaged carbon stock of tree plantations or crop-fallow systems ($C_{time\text{-}averaged}$), time at start of rotation (T_0), time to reach maximum carbon stock (T_{max}), rotation time (T_r) and time in fallow phase (T_f). Tree based system and crop-fallow system were adapted and revised from ASB (1999), Palm et al. (2005), whereas rubber based system was developed from the present study to illustrate that above ground carbon stocks were different for lowland and highland rubber plantations.

Table S2.1. Specifications of land-use/land-cover maps used in current study.

LULC maps	Preparation based on	Original spatial Resolution (m)	Satellite data acquisition dates	Source
1989	Field survey	-	-	Tao (1989)
2007	SPOT	10	2006-05-17	LILAC project, Gibreel et al. (2014)
	IKONOS	4	October-December 2007	
	Field survey	-	-	
2012	Rapideye	5	2012-11-03, 2012-05-03, 2013-01-19, 2013-06-13	SURUMER project
	Field survey	-	-	

References:

Gibreel, T.M., Herrmann, S., Berkhoff, K., Nuppenau, E., Rinn, A., 2014. Farm types as an interface between an agroeconomical model and CLUE-Naban land change model: Application for scenario modelling. Ecol. Ind. 36, 766-778.

LILAC: Living Landscapes China http://lilac.uni-hohenheim.de/en/index.php

SURUMER: https://surumer.uni-hohenheim.de/

Tao, G.D., 1989. Vegetation survey of Nabanhe basin. In: Investigation Group of Nabanhe Watershed Nature Reserve, Synthetical Investigation Report of Nabanhe Watershed Nature Reserve. Environmental Monitoring Station Press of Xishuangbanna, Xishuangbanna. pp. 18-31.

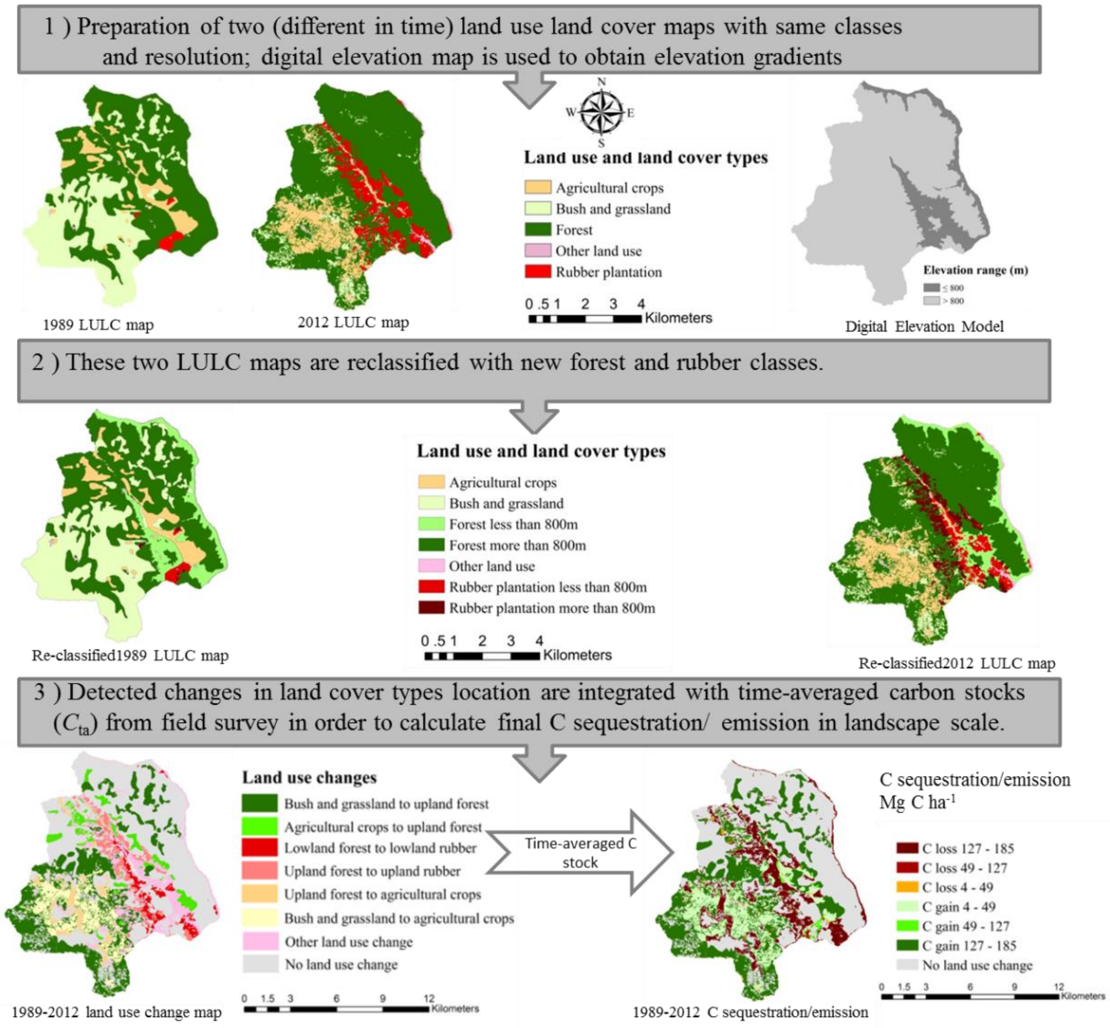

Figure S2.2. GIS processing of land use maps to obtain carbon sequestration or emission during 1989-2012. Detailed land use change pattern within each functional zone during 1989 to 2012 is in the Table S2.2

Table S2.2. Land use conversion in different functional zones in Naban River Watershed National Nature Reserve, Xishuangbanna, China, and its carbon emission or sequestration effects during 1989-2012.

Functional zones	Elevation below 800 m			Elevation above 800 m			Total
	Change pattern	**Area change percentage (%)**	**C emission/ sequestration (Tg)**	**Change pattern**	**Area change percentage (%)**	**C emission/ sequestration (Tg)**	**C emission/ sequestration (Tg)**
Core zone	Bush and grassland to forest	0.66	0.005	Forest to bush and grassland	1.11	-0.007	0.115
				Agricultural crops to forest	0.09	0.001	
				Bush and grassland to forest	19.62	0.117	
Buffer zone	Forest to rubber	3.45	-0.029	Forest to rubber	4.41	-0.038	0.115
	Forest to other land use	0.91	-0.011	Forest to bush and grassland	0.11	-0.001	
	Forest to agricultural crops	0.44	-0.005	Agricultural crops to rubber	2.96	0.004	
	Forest to bush and grassland	0.16	-0.002	Bush and grassland to forest	5.06	0.052	
	Bush and grassland to forest	0.22	0.003	Agricultural crops to forest	9.39	0.093	
	Agricultural crops to rubber	4.21	0.014				
	Agricultural crops to forest	2.86	0.034				
Experimental zone	Forest to rubber	2.87	-0.057	Forest to rubber	4.72	-0.095	0.414
	Forest to agricultural crop	0.33	-0.009	Forest to agricultural crops	4.84	-0.112	
	Rubber to forest	0.49	0.010	Forest to bush and grassland	1.70	-0.041	
				Forest to other land use	0.39	-0.010	
				Rubber to forest	0.14	0.003	
				Other land use to forest	0.12	0.003	
				Bush and grassland to rubber	2.29	0.007	
				Agricultural crops to forest	3.44	0.079	
				Bush and grassland to forest	28.15	0.649	

Table S2.3. Comparison of published studies on carbon stocks in rubber plantations with current research. The dynamics of above ground carbon stock (y, Mg C ha^{-1}) as a function of stand age (x, year), maximum carbon stock (C_{max}) and estimated time-averaged carbon stock ($EstC_{ta}$) in tons per hectare are shown together with site description.

Aboveground carbon vs time	**Site location**	**Plantation age**	**Elevationm a.s.l.**	**Plot No.**	C_{max}	$EstC_{ta}$	**Source**
$Y_{stem} = -0.0723x^2 + 7.8964x - 42.018$	XSBN-1 [a], China	7-47	565-640	15	110 [b]	30	Tang et al. (2009)
$Y_{branch} = -0.0205x^2 + 2.1776x - 11.453$							Tang et al. (2009)
$Y_{leaves} = 2.6981 \ln x - 4.5488$							Tang et al. (2009)
$Y = 122.89/(1+17.34\exp(-0.13x))$	XSBN-2, China	5-47	570	10	123	28	Song et al. (2014)
$Y = 205.82/(1+13.12\exp(-0.21x))$	XSBN-3, China	5-26	550-800	10	103	53	Song and Zhang. (2010)
$Y = 139.76/(1+17.83\exp(-0.14x))$	XSBN-4, China	5-26	950-1050	5	70	17	Song and Zhang. (2010)
$Y = 147.83/(1+10.76\exp(-0.11x))$	NRWNNR-1, China	5-35	620-800	11	148	40	This study [c]
$Y = 50.30/(1+34.31\exp(-0.30x))$	NRWNNR-2, China	4-25	800-1050	12	50	28	This study [c]
$Y = 142.27/(1+13.31\exp(-0.19x))$	Thailand	1-26	NA [d]	723	142	52 [e]	Petsri et al. (2013)
$Y = 174.194\exp(-5.033\exp(-0.125x))$	Western Ghana	2-14	NA	25	174	61	Wauters et al. (2008)
$Y = 58.286\exp(-9.722\exp(-0.179x))$	Mato Grosso, Brazil	15-26	500	34	58	21	Wauters et al. (2008)
$Y = 49.11\exp(-16.186\exp(-0.267x))$	Brazil	4-25	NA	80	49	28	Wauters et al. (2008)

[a] XSBN stands for Xishuangbanna.

[b] The rubber trees above ground carbon stock was estimated as the sum of stem, branches and leaves. The maximum carbon stock was calculated by using stand age as 47 year. For C_{ta} rotation length 25-year was used for calculation, same as other studies.

[c] Only the present study took consideration of understory biomass and necromass, other studies based carbon estimates on rubber trees biomass only.

[d] Elevation was not mentioned. We assume the elevation was in the range of 200-500m.

[e] In this study, only whole tree (AGB+BGB) growth regression available, we used the averaged root shoot ratio 0.23 for conversion, and obtained the estimated $EstC_{ta}$ was 52 Mg C ha^{-1}.

Chapter 3

Rubber tree allometry, biomass partitioning and carbon stocks in mountainous landscapes of sub-tropical China

Chapter 3 Rubber tree allometry, biomass partitioning and carbon stocks in mountainous landscapes of sub-tropical China[2]

Xueqing Yang[a,b,c], Sergey Blagodatsky[a,d], Feng Liu[e], Philip Beckschäfer[f], Jianchu Xu[c], Georg Cadisch[a]

[a] *Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Garbenstrasse 13, Stuttgart 70593, Germany*

[b] *Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China*

[c] *World Agroforestry Centre (ICRAF), China & East Asia Office c.o. Kunming Institute of Botany, Heilongtan, Lanhei Road No.132, Kunming 650201, China*

[d] *Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences, 142290 Pushchino, Russia*

[e] *Bureau of Naban River Nature Reserve, Yuanlin alley 19#, Jinghong, 666100, China*

[f] *University of Göttingen, Chair of Forest Inventory and Remote Sensing, Büsgenweg 5, Göttingen 37077, Germany*

2 **This chapter has been reprinted from:**

Yang, X.Q., Blagodatsky, S., Liu, F., Beckschäfer, P., Xu, J.C., Cadisch, G., 2017. Rubber tree allometry, biomass partitioning and carbon stocks in mountainous landscapes of sub-tropical China. Forest Ecology and Management 404, 84-99. (https://doi.org/10.1016/j.foreco.2017.08.013 Elsevier B.V. All rights reserved.)

The original publication is available at:
https://www.sciencedirect.com/science/article/pii/S0378112717305480?via%3Dihub

Abstract

Expansion of rubber plantations into sub-optimal environments has been a dominating land conversion in continental South-East Asia in the last decade. Regional evaluation of the carbon sequestration potential of rubber trees depends largely on the selection of suitable allometric equations and the biomass-to-carbon conversion factor. Most equations are age-, elevation-, or clone-specific, and their application therefore gives uncertain results at the landscape level with varying age groups, elevation ranges, and clone types. Currently, for rubber-based systems, none of the allometric equations takes environmental factors (e.g. climate, topographic condition, soil properties, and management scheme) into consideration to allow pan-tropical usage. Against this background, 30 rubber trees with a root profile of up to 2 m were destructively harvested and 882 rubber trees were measured non-destructively in 27 plots, covering rotation lengths of 4-35 years, elevation gradients of 621-1,127 m, and locally used clone types (GT1, PRIM600, Yunyan77-4) in mountainous South Western China. Allometric equations for aboveground biomass (*AGB*) estimations considering diameter at breast height (*DBH*), tree height (*H*), and wood density were superior to other equations. A simpler model with similar performance ($AGB = 0.0419DBH^{2.316}H^{0.478}$) can be used if tree-specific wood density is not available. For belowground biomass (*BGB*) a model using only *DBH* can provide a robust prediction ($BGB = 0.207DBH^{1.668}$). We also tested goodness of fit for the recently proposed pan-tropical forest model, which includes a bioclimatic factor *E*, combining indices of temperature and precipitation variability and drought intensity. Prediction of *AGB* by the model calibrated with the harvested rubber tree biomass and wood density was more accurate than the results produced by the pan-tropical forest model adjusted to local conditions. The relationships between *DBH* and height and between *DBH* and biomass were influenced by tapping, therefore biomass and C stock calculations for rubber have to be done using species-specific allometric equations. Based on the analysis of environmental factors acting at the landscape level, we found that above- and belowground carbon stocks were mostly affected by stand age, soil clay content, aspect, and planting density. Increasing planting density to > 570 trees per ha according to the regional plantation management strategy had a negative impact on aboveground carbon stock of old rubber plantations. The integration of bioclimatic and regional management factors is a further approach to build widely applicable biomass models for pan-tropical rubber-based systems. The results of this study provide reference for reliable carbon accounting in other rubber-cultivated regions.

Keywords

forest plantations, aboveground biomass, belowground biomass, root-to-shoot ratio, carbon stock

3.1 Introdution

In many tropical regions, land use change has caused uncertainties in global carbon stocks accounting. This has been mainly attributed to changes in plant and soil carbon stocks during conversion of natural forests into economic plantations, e.g. oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis* Müll. Arg), and eucalypt (*Eucalyptus grandis)* (Houghton and Goodale 2004, Houghton 2005). The dramatic expansion of monoculture plantations has been blamed for high rates of deforestation and forest degradation in South East Asian countries (Fox, 2000; Koh and Wilcove, 2008; Ziegler et al., 2009; Li and Fox, 2012; Brockerhoff et al., 2013). Several market-based mechanisms were proposed as guidance on reduction of emissions from deforestation and forest degradation (REDD), sequestration of carbon through reforestation, and maintenance of existing forests (REDD+, Clean Development Mechanism) in tropical regions (Myers, 2007; Angelsen, 2009). However, implementation of these programs has not been straightforward (Van Noordwijk et al., 2012; Murray et al., 2015). Particularly, analysis of substitution of traditional swidden land by rubber plantations in Montane Mainland Southeast Asia (MMSEA) reflected how land use change might pose varying impacts on carbon emissions, farmer livelihoods and regional environmental services (Fox et al., 2014). To make emission reduction incentives widely applicable, a reliable and efficient tree carbon stock assessment is required.

Rubber is a perennial tree originating from the Amazon basin in South America; its historical habitat is distributed in the equatorial zone between 10°N and 10°S. Suitable natural cropping climates for rubber in the mainland of South East Asia include portions of southern Thailand, southeastern Vietnam, and southern Myanmar, other new expansion regions mainly located in Montane Mainland Southeast Asia (Fox and Vogler, 2005). With increasing worldwide natural rubber consumption and economic development, in the 1950s, the Chinese government initiated the “Decision on Cultivating Rubber Trees” for national defense and industrial demands. This strategy promoted the cultivation of rubber plantations in non-traditional environments, expanding as far north as 22° latitude in China, with cooler winter temperatures and distinct dry seasons (Xu et al., 2005). Currently, rubber plantations mainly serve as an important source of natural latex (review by Venkatachalam et al., 2013). Rubber trees are also used for wood products and furniture (Zhang et al., 2009). Additionally, plant biomass provides a bioenergy source used for heating (Krukanont and Prasertsan, 2004) and seed oil, which is used in various industries (Zhu et al., 2014). The massive expansion of rubber plantations has also negative impacts, such as increased carbon emissions, decreased biodiversity, habitat loss, and food security threat (Hu et al., 2008; Ziegler et al., 2009; Fu et al., 2010; Song et al., 2014; Cotter et al., 2017). In tropical countries, the feasibility of promoting biodiversity co-benefits with high carbon stocks and the optimization of rubber’s economic benefit for local livelihoods have been tested through various carbon trading schemes (Yi et al., 2014a; Villamor et al., 2014). Considering that more than 2.1 million ha of montane mainland Southeast Asia are occupied by rubber plantations (Fox et al., 2014), precise tree biomass estimation in these mountainous regions is a premise for landscape level rubber-based system carbon stock quantification.

The most accurate method for tree biomass assessment is harvesting the whole tree, with further separation into its components. Then, each component needs to be oven dried and weighted to determine its biomass. The carbon content of each component can be determined to quantify the total carbon stock of the biomass (Ketterings et al., 2001). Nevertheless, this approach can be applied only to a limited extent because of the time and labor-consuming procedure of sampling and due to its destructive nature. Instead of direct harvesting, tree biomass could also be modeled using allometric equations, that link easily measurable tree parameters, such as diameter at breast height (*DBH*), tree height (*H*), crown area (*CA*), wood density (ρ), etc., with biomass through linear or non-linear model fitting (Picard et al., 2012). Most existing allometric equations for rubber trees use *DBH* for biomass prediction (Jia et al., 2006; Tang et al., 2009; Sone et al., 2014). Cross-sectional area of the rubber tree trunk at breast height (basal area, *BA*) (Schroth et al., 2002) and trunk circumference (girth, *G*) (Shorrocks et al., 1965; Dey et al., 1996; Wauters et al., 2008) are also commonly applied in allometric equations. Some studies tried to improve prediction through allometric equations by including additional parameters, e.g. tree height (Jia et al., 2006; Tang et al., 2009; Sone et al., 2014), crown area, and wood density (Wauters et al., 2008). However, the selection and application of allometric equations for rubber trees faces many challenges. The restricted geographic areas of studies on allometric equations limit a wider application because of the uncertain transferability of the estimated parameters (Yuen et al., 2013; Yuen et al., 2016). Trunk circumference or diameter measurements made at different heights further hamper the comparison of allometric equations and the transferability of results. Previous studies used 1.2 m (Sone et al., 2014), 1.3 m (Schroth et al., 2002; Tang et al., 2009), 1.5 m (Shorrocks et al., 1965; Dey et al., 1996; Jia et al., 2006), or 1.7 m (Wauters et al., 2008) for stem diameter measurement. Evidence from existing studies showed that rubber tree stand age was the main predictive factor for tree biomass (Tang et al., 2009; Song and Zhang., 2010; Petsri et al., 2013; Song et al., 2014). Moreover, climatic conditions (wetness) (Wauters et al., 2008; Munasinghe et al., 2014), elevation, slope and aspect (Jia et al., 2006; Yi et al., 2014a; Zhai et al., 2014; Yang et al., 2016), soil fertility and texture composition (Samarappuli et al., 2000), tapping activities during the growing season (Silpi et al., 2006), planting density (Wauters et al., 2008), and tree clone type

(Chaudhuri et al., 1995) also impact on tree biomass partitioning and girth development. The integrative relationship between rubber tree biomass and its surrounding environment (climatic condition determined by topographic location, soil properties, and management scheme) has not yet been established systematically. Thus, application of allometric equations under environmental conditions that differ from the conditions in the region, where equations were derived, needs to be performed with caution. Besides, few allometric equations are available for belowground biomass (*BGB*). Root biomass comprises around 17% of total rubber biomass based on the root-to-shoot ratio; therefore, omission or incorrect estimation of root biomass will bias biomass and potential carbon stock assessments of rubber plantations (Yuen et al., 2013).

In the context of China, only few allometric equations are available for rubber tree *AGB* and *BGB* estimations (Jia et al., 2006; Cheng et al., 2007; Tang et al., 2009). Most of them were established for age-, elevation-, or clone-specific groups, so that applying these equations to uneven-aged multi-clone stands across various elevations is risky. , and the upscaling of model results to heterogeneous landscapes with various environmental influences can be problematic. Against this background, we attempted to derive generic allometric equations for rubber tree *AGB* and *BGB*, with consideration of various stand ages, elevations, and mixed clone types in a rubber planting area located in a mountainous landscape. The specific aims of this study were: (1) to quantify rubber tree biomass production and partitioning in a chronosequence in a mountainous landscape of sub-tropical China; (2) to develop generic allometric equations for rubber tree *AGB* and *BGB*; and (3) to upscale tree level biomass to plot level carbon stocks and to explore the influence of environmental factors on them. The results will be useful for providing reliable rubber tree biomass evaluations in mountainous landscapes over a wide range of environmental conditions. Comparison of carbon stocks in rubber plantation with those in other land use types provides a basis for land management decisions and for selection of future mitigation strategies dealing with environmental changes.

3.2 Methods

3.2.1 Study site

The Naban River Watershed National Nature Reserve (Naban Reserve) is located in the Dai Autonomous Prefecture of Xishuangbanna, Yunnan, China. The total protected area is 26,660 ha (22°04′ - 22°17′ N, 100°32′ - 100°44′ E), with an elevation range from 539 to 2,304 m. The reserve has distinct dry (November-April) and rainy seasons (May-October). Annual rainfall varies from 1,200 - 1,700 mm and annual mean temperature range is 18 - 22°C (YEPB, 2006). The major soil types are Ferralsols (Apel, 1996), whereas minor soil types are Regolsols (FAO/UNESCO, 1998). The reported rubber plantation area in Naban Reserve increased from 338 ha in 1989 to 2,858 ha in 2012 (Yang et al., 2016). Plantations are mainly smallholder-owned, only 150 ha belong to state-owned enterprises. Rubber trees are cultivated in rows on terraced benches and have an average intra-row tree spacing of 2 - 3 m; the horizontal distance between two adjacent terraces with one row of trees per terrace is 5 - 7 m, depending on the slope of the hill. The dominant rubber clones planted in the study region are GT1 and RRIM 600, similar to those of other regions of Xishuangbanna (Yi et al., 2014b). Clone GT1 can resist cold stress and diseases, but gives lower yield of latex (Luo et al., 2012), while RRIM600 provides a higher latex yield, but is sensitive to cold stress and diseases (Priyadarshan et al., 2005). The newly developed clone type Yunyan77-4, which shows better resistance to low temperatures and is currently often planted at higher elevations occurs in the study site as well (Chen et al., 2008). Farmers living in Naban Reserve start tapping of rubber trees when the tree girth reaches 50 cm in circumference (16 cm diameter) at a height of 1.3 m from the ground. In most circumstances, rubber tree girth can reach adequate size for tapping after seven or eight years, while trees cultivated at higher elevations require more time. Farmers tap latex from March to November, with a tapping frequency of every two days (Golbon et al., 2015). Chemical fertilizers (NPK-compounds) are applied in spring (April) and autumn (September) by using the fertilizer pit approach (Dong et al., 2015). Understory vegetation is cleared twice per year using herbicides or manual cutting.

3.2.2 Field survey

To gain an overall understanding of rubber plantation age distribution in the study area, we used a land-use/cover map (accessed from the SURUMER project: Sustainable Rubber Cultivation in Great Mekong Region, cited in Yang et al. (2016)) to identify rubber plantation areas and conducted a field survey in December 2012. Historical land-use, stand age, and clone type information for each plot were recorded by interviewing local farmers. The surveyed plots covered the traditional suitable growth area for rubber (< 800 m) as well as the marginal area (> 800 m), with consideration of varying rubber stand ages ranging from 4 to 35 years. Destructive sampling of 30 rubber trees was applied to obtain tree biomass production and partitioning information; the sampled trees were selected in different plantations in Naban Reserve to represent the landscape heterogeneity. Both tree and plot level assessments were carried out within smallholder rubber plantations with similar fertilization management and herbicide usage. Measurements were conducted during 2013-2014, sampled trees were selected in different locations with sampled plots in landscape scale (Figure 3.1, Table 3.1).

3.2.3 Tree sampling

Ground surveyed rubber plantations' age distribution provided a priori information to guide our tree sampling, we harvested 6-, 10-, 15-, 20-, and 25-year-old trees at two elevation classes (above and below 800 m); for each age group in each elevation class three trees were sampled (Table 3.1). We selected healthy and vigorous trees, not deformed by disease, excluding heavily defoliated, broken topped or hollow trees (Snowdon et al., 2002). We measured tree height (*H*) and *DBH* (at 1.3 m aboveground) for each selected tree. Trees were separated into stems, branches, foliage, fruits, coarse roots (taproot and lateral roots with diameter larger than 5 mm), and fine roots (diameter less than 5 mm) (Figure 3.2). To quantify root biomass distribution across

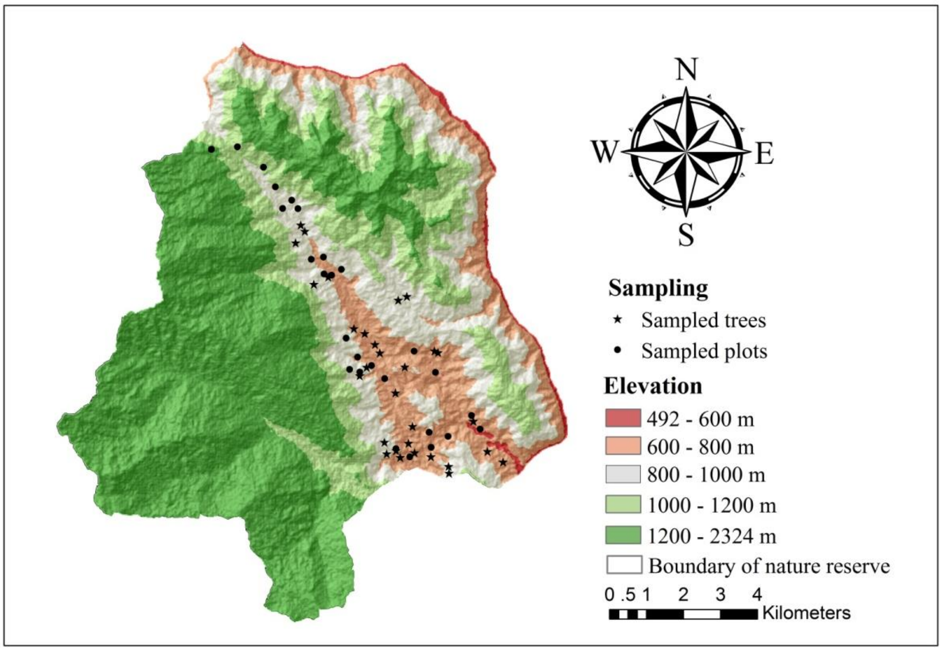

Figure 3.1. Sampling of rubber plantations in Naban Resrve, China. Rubber plantations are primarily distributed at low to medium elevations in the main valley of the nature reserve (800-1200 m), the age of the surveyed trees covers the rotation length of rubber plantations (4-35 year).

Table 3.1. Harvested rubber trees and sampled plots in landscape of Naban Reserve. The basic tree parameters condition at various stand age along elevation gradients were displayed.

Elevation class (m)	**Age class (year)**	**Age** (mean ± S.D. **(year))**	**DBH** (mean ± S.D. **(cm))**	**Height** (mean ± S.D. **(m))**	**Number of plots**	**Number of harvested trees[a]**
Low altitude (< 800)	Young (<7)	6 ± 0.4	13.0 ± 3.6	11.8 ± 2.3	2	3
	Mid-aged (7-20)	13 ± 4.1	15.3 ± 4.8	12.8 ± 2.9	8	9
	Old (>20)	27 ± 5.6	24.3 ± 7.1	17.7 ± 3.9	4	3
High altitude (≥ 800)	Young (<7)	6 ± 0.7	8.0 ± 2.7	7.5 ± 2.1	5	3
	Mid-aged (7-20)	14 ± 6.1	15.0 ± 3.9	12.0 ± 3.0	6	9
	Old (>20)	25 ± 0.9	21.8 ± 5.0	15.5 ± 3.0	2	3
Total					27	30

[a] The harvested rubber trees contain age class of 6-, 10-, 15-, 20-, and 25-year-old at two elevation classes (above and below 800 m), for each age class we have three repeated samples. Here we classified age class of 6-year as young rubber (<7), age class of 10-, 15- and 20-year old as mid-aged rubber (7-20), age class of 25-year old as old-aged rubber (>20).

the soil profile, the soil-pit method was applied (Park et al., 2007). We sampled a quadratic pit of 2 × 2 m around a rubber tree. Although this pit size might not fully represent root biomass across the terraces, we kept it uniform to make results comparable in view of the varying inter-row distances and slopes in the area. The roots were collected along a 2 m deep soil profile, which was divided into 10 layers of 20 cm sampling depth each. The extracted coarse and fine roots from each soil layer were sorted, cleared from soil, and fresh weight measured. Sub-samples of coarse- and fine roots were oven-dried until constant dry weight was reached. Sub-samples of rubber tree components were weighted wet within three days and dried at 85℃ for two days to obtain tissue-specific wet-to-dry conversion factors. Wood samples were taken with an increment borer (SUUNTO, 400 mm, 2N, Finland) from cross-sectional diameter parts (with 3cm thickness, collected from destructively harvested trees) of tap roots, at breast height (1.3 m), and at 2 m distances along the stem (i.e. at 1.3 m, 3.3 m, 5.3 m, etc.) up to the top of the tree. Wood density was then determined as the ratio of dry weight of the cored material to the volume of the core. The averaged value of wood samples was used to represent whole tree wood density. Tree crown area (*CA*) was calculated based on crown diameter (*CD*) from $CA = (\pi \times CD^2)/4$; here, *CD* was obtained by measuring the longest and shortest extent of the crown and averaging these values (Blozan, 2006). Carbon concentration of biomass for individual harvested trees was determined by element analysis of samples from tree components, using an Elementar Vario max CNS analyzer (German Elementar Company, 2003). The C concentration together with measured tree density was then used to convert *AGB* and *BGB* into C mass.

3.2.4 Soil and plot level tree analysis

Twenty-seven sampling plots (20 × 25 m^2) were established in the surveyed landscape, a stratified sampling approach was applied to cover rubber stand ages from 4 to 35 years distributed at two major elevation levels (details of the sampling approach can be found in Yang et al. (2016)). Mean annual temperature (*MAT*) and mean annual

Figure 3.2. Destructive sampling of rubber trees. a) Young rubber tree roots distribution across soil profile; b) oven-dried tree component sub-samples (from top left to bottom right): lateral roots (diameter > 2 cm), lateral roots (diameter ⩾ 5mm and ⩽ 2 cm), lateral roots (< 5 mm), leaves, cross-sections of tree stems from above ground 10 cm to tree crown, major branches (diameter ⩾ 2.5 cm), twigs (diameter < 2.5 cm), seeds; c) harvested tree taproot.

precipitation (*MAP*) were extracted for each plot from the WordClim dataset (1950-2000) (www.worldclim.org), with a spatial resolution of 1 km (Hijmans et al., 2005). In the field, we recorded topographic information (slope, aspect, elevation) and number of stems. Aspect was measured clockwise in degrees and defined as: east facing (46-135°), south facing (136-225°), west facing (226-315°), and north facing (316-45°). From each of the three planting terraces commonly contained in each plot we randomly selected two trees for height measurement (*n*=6). During the seasonal tree defoliation period (December) tree height (below 10 m in height) was measured with a telescope height measuring pole; while for larger trees the height measurement was carried out using a Nikon Forestry 550D laser rangefinder–clinometer (Nikon Vision Co., Ltd.), and averaged to mean height per plot.

Soil samples at 0 - 10 cm, 10 - 20 cm, and 20 - 30 cm depth were collected with a soil auger to determine chemical properties (see below). Soil bulk density was estimated by triple sampling with a stainless-steel core (200 cm^3 volume) at 10 cm soil depth intervals. The dried soil samples were sieved using a 2 mm mesh sieve to remove vegetation and gravel. Five soil samples were mixed per depth, resulting in three composite soil samples per plot. Soil texture was assessed following Bouyoucos (1962). Concentrations of total C and N were determined with the Elementar Vario max CNS analyzer (German Elenmentar Company, 2003). The concentration of soil organic C (%) was determined using the wet oxidation procedure with $K_2Cr_2O_7$ (Nelson and Sommers 1982). Subsequently, soil carbon stocks (Mg C ha^{-1}) at each depth interval were calculated based on bulk density (Mg m^{-3}) and soil layer thickness (cm). Total topsoil (0-30 cm) carbon stocks were calculated as the sum of the three soil depth intervals (Nelson et al., 1982; Pearson et al., 2005).

3.2.5 Generic allometric equations for AGB and BGB

We used log-transformed linear functions for the description of power ($y = ax^b + \varepsilon$) relationships between response variable (y) and predictor variable (x) for tree biomass estimation (Brown et al., 1989; Chave et al., 2005):

$$\ln(y) = \ln(a) + b\ln(x) + \varepsilon, \tag{3.1}$$

where y stands for tree biomass (kg), x is the measured tree parameter (e.g. *DBH*), a is the intercept coefficient, and ln (a) = α, b is the scaling exponent; both a and b were estimated from ordinary least squares procedures and logarithmic transformation corrected for heteroscedasticity, the ε is the regression error.

Concerning rubber tree biomass estimation, the commonly adopted predictive variables are *DBH* and girth (*G*) (Chaudhuri et al., 1995; Dey et al., 1996; Rojo-Martínez et al., 2005; Jia et al., 2006; Tang et al., 2009; Wauters et al., 2008; Chantuma et al., 2012; Sone et al., 2014), tree height (*H*) (Wauters et al., 2008), and integrative tree height and *DBH* (DBH^2H) (Rojo-Martínez et al., 2005; Jia et al., 2006; Tang et al., 2009; Munasinghe et al., 2014; Sone et al., 2014). Other variables such as crown area (*CA*) and wood density (ρ) have not been tested in rubber biomass estimations so far, although studies from Kuyah et al. (2012a, 2012b) report on improved model fitting by adding *CA* and ρ for estimating standing tree *AGB* and *BGB* distributions of other tree species in agricultural landscapes. Thus, we introduced the above-mentioned tree parameters into the following models for *AGB* and *BGB* estimations:

$$\ln(y) = a + b\ln(DBH) + \varepsilon \tag{3.2}$$

$$\ln(y) = a + b\ln(DBH^2H) + \varepsilon \tag{3.3}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(H) + \varepsilon \tag{3.4}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(\rho) + \varepsilon \tag{3.5}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(CA) + \varepsilon \tag{3.6}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(\rho) + d\ln(CA) + \varepsilon \tag{3.7}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(H) + d\ln(\rho) + \varepsilon \tag{3.8}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(H) + d\ln(CA) + \varepsilon \tag{3.9}$$

$$\ln(y) = a + b\ln(DBH) + c\ln(H) + d\ln(\rho) + e\ln(CA) + \varepsilon \tag{3.10}$$

Using the logarithmic form of allometric equations may produce systematic underestimation of the dependent variable *y* when converting the estimated ln (*y*) back to the original untransformed scale *y*. To correct this bias, a correction factor (*CF*) for each regression equation was computed, following Baskerville (1972) and Sprugel (1983):

$$CF = \exp\left(\frac{RSE^2}{2}\right) \tag{3.11}$$

where RSE is the models' residual standard error, obtained from the regression procedure. Then the original untransformed scale *y* with *CF* could be obtained by $y = (CF*a)\, x^b + \varepsilon$. We used the following criteria to evaluate the different models: adjusted coefficients of determination (adj. R^2) and Akaike information criterion (AIC) (Akaike, 1981) - for model fitness, the relative error (RE %) and root mean square error (RMSE) - for testing estimation error distribution. The most appropriate equation was the one with the highest adj. R^2, lowest AIC value, and an RE% or RMSE close to zero. Kuyah et al. (2012a and 2012b) recommended to give more weight to bias and RMSE rather than adj. R^2 and AIC when deciding on the final optimum model. The expressions for calculating RE% and RMSE were as follows:

$$RE\% = \left\{ \frac{(\hat{y}_i - y_i)}{y_i} \right\} \times 100 \tag{3.12}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}} \tag{3.13}$$

where $\hat{y}_i$ and y_i are the predicted and observed values of biomass and n is the total number of data points used in fitting the model.

3.2.6 Comparison of established equations with existing regional models to detect biomass estimation uncertainty

To compare our models with published equations for rubber trees, for both *AGB* and *BGB*, we selected biomass equations applying *DBH* or parameters derived from *DBH* (e.g. *G*, *BA*), as these models are widely used in tropical regions (Supplementary Material Table S3.1 and Table S3.2). For *BGB* models, we also considered the meta-analysis-derived root-to-shoot ratio (Yuen et al., 2013). Existing allometric equations did not always include a *CF* value for correcting bias from log-transferred regression, and the *CF* derived from small sample sizes might cause potential bias (Flewelling and Pienaar 1981). Therefore, we followed the strategy of previous studies (Jenkins et al., 2003; Henry et al., 2011) and did not use *CF* when the authors originally did not include them in their allometric equations. If *DBH* at 1.3 m was not available from published data, we transformed the *DBH* measured at 1.5 m or 1.7 m to the *DBH* at 1.3 m, using the empirically derived average diameter decrease with height function, 0.0186 cm decrease per cm, similar to the 0.0146 cm obtained by Kotowska et al. (2015). This former value was derived from the direct measurements of tree diameter made for a tree height of 1.3 - 3.3 m in the current study (n = 30 trees). Subsequently, the measured data of *AGB* and *BGB* from the current study were plotted against other existing models, to visualize bias and error distribution in order to better understand the models' predictive performance. Regression analysis was carried out in R 3.1.0 (R Development Core Team, 2014). The best parameters for allometric equations were found using linear models (lm, package: 'stats') and models were compared using the Akaike information criterion (AIC) in a stepwise algorithm (stepAIC, package: 'MASS').

To investigate the uncertainty resulting from the application of existing allometric equations (Jia et al., 2006; Tang et al., 2009) and the application of the IPCC reported C conversion factor (0.5) in biomass, we compared carbon stock estimations in our previous work (Yang et al., 2016) with our updated model results and thereafter evaluated the carbon stock difference between the two methods.

Recently, Chave et al. (2015) introduced a bioclimatic stress variable *E* into pan-tropical allometric equations that improved tree biomass estimations as compared to previous models. Adding this bioclimatic stress variable, calculated from temperature seasonality, precipitation seasonality and maximum climatological water deficit, could well reflect the climatic conditions of various regions. We tested the applicability of the pan-tropical diameter-height model (Equation 6a in Chave et al., 2015) and its *AGB* estimation model (Equation 7 in Chave et al., 2015) for rubber plantation systems by extracting the bioclimatic stress variable *E* from their gridded layer at 2.5 arc minutes resolution (~ 5 km^2) (http://chave.ups-tlse.fr/pantropical_allometry.htm) and our harvested tree dataset with *DBH* and wood density. We also parametrized allometric equations with the bioclimatic stress factor *E* using biomass data gathered in the current study and compared them with established models without *E* (e.g. Equation 3.2). Moreover, to detect the variation of rubber *AGB* between traditional rubber growing areas and their expansion regions, we used trees with the same *DBH* value of 35 cm (normally close to late-rotation length stage) and compared *AGB* distribution along *E* gradients by fitting equations presented in

Supplementary Material Table S3.1.

3.2.7 Standing tree biomass carbon stock at landscape level and influencing factors

By applying allometric equations, namely Equation (3.4) and Equation (3.2) for *AGB* and *BGB* calculation respectively, we calculated per plot carbon stocks based on tree height, *DBH*, number of stems (Yang et al., 2016), and C content of biomass (see section 3.3.2).

The differences in *AGC* and *BGC* between highland and lowland areas were estimated using one-way ANOVA. The influence of environmental factors (e.g. climate, topography, soil, management) on *AGC* and *BGC* was tested with Spearman´s correlation analysis. We considered MAP (mean annual precipitation, mm); MAT (mean annual temperature, °C); Elevation (meter.a.s.l); Age (plantation stand age, year); Slope (°); Aspect (°); Density (plantation planting density, trees ha^{-1}); Sand (soil sand concentration percentage, %); Clay (soil clay concentration percentage, %); Silt (soil silt concentration percentage, %); C/N (dimensionless unit); SOC (soil organic carbon, Mg ha^{-1}). Subsequently, the classification and regression tree (CART) model (Breiman, 1984) was applied to identify the critical environmental variables that significantly influenced biomass carbon stocks at the plot level (Sun et al., 2013; Liu et al., 2014). Compared to the traditional commonly applied statistical approach (e.g. linear regression), CART is superior in dealing with nonlinear relationships, or high-order interactions to find controlling factors in complex ecological data (Breiman et al., 1984). Variables used for the first binary CART splits are considered as the most determining factors, explaining the highest variance in the dependence variable (De'ath and Fabricius, 2000). The CART model calculates threshold values for each driver and quantifies possible interactions between factors necessary for decision making. Once a full CART model has been built, it is necessary to decide how much of the model to retain if the tree is too large or complex. The complexity parameter (CP) is used to indicate the smallest relative error of a pruned decision tree for presenting the complete dataset; it can save computing time by avoiding unnecessary tree splits. We set the complexity parameter (CP) to 0.0001 to include all environmental factors and then used the minimum x-error (cross validation error) corresponding CP value to achieve an optimum tree (pruned decision tree) to identify dominant factors. A tenfold cross-validation was performed by default to evaluate the reliability of the CART generated decision tree. The detailed operating process can be found in the R guideline book (R Development Core Team, 2014). The correlation test was conducted by using the correlation function "psych" (R package). The CART model was generated by the 'rpart' function, control function, and prune function (R package "rpart", "rpart.plot").

3.3 Results

3.3.1 Tree biomass partitioning

Stem biomass accounted for 56.8% of the total biomass when averaged over the 30 harvested trees, while fruits and fine roots accounted for less than 2% (Figure 3.3, details see Supplementary Table S3.3). Between the age 7 to 25 years, the stem fraction increased from 48 to 61%. Similarly, the branch fraction increased, while fractions of leaves, fruits, coarse and fine roots decreased with age (Figure 3.3). The proportion of *AGB* (stem, branches, foliage, and fruits) to total tree biomass increased from 78% in six-year-old trees to 86% in 25-year-old trees, while *BGB* (coarse roots and fine roots) decreased from 22 to 14%, respectively. Coarse and fine roots were mainly distributed in the top 60 cm of the soil, amounting to nearly 80 and 70% of root biomass, respectively, in the 2 m soil profile (Figure 3.4). Total dry mass increased by more than five times from age 6 (70 kg tree^{-1}) to 25 (360 kg tree^{-1}) years. Average root-to-shoot ratio (*R/S*) for rubber trees in 6, 10, 15, 20, and 25-year-old plantations was 0.29, 0.26, 0.21, 0.16, and 0.15, respectively. Overall average root-to-shoot ratio was 0.215 ± 0.07 (SD). We described the *R/S* development of standing trees with the power function:

$$R/S = 4.105DBH^{-1.02} \tag{3.14}$$

with P < 0.0001, RSE = 0.166, R^2 = 0.72.

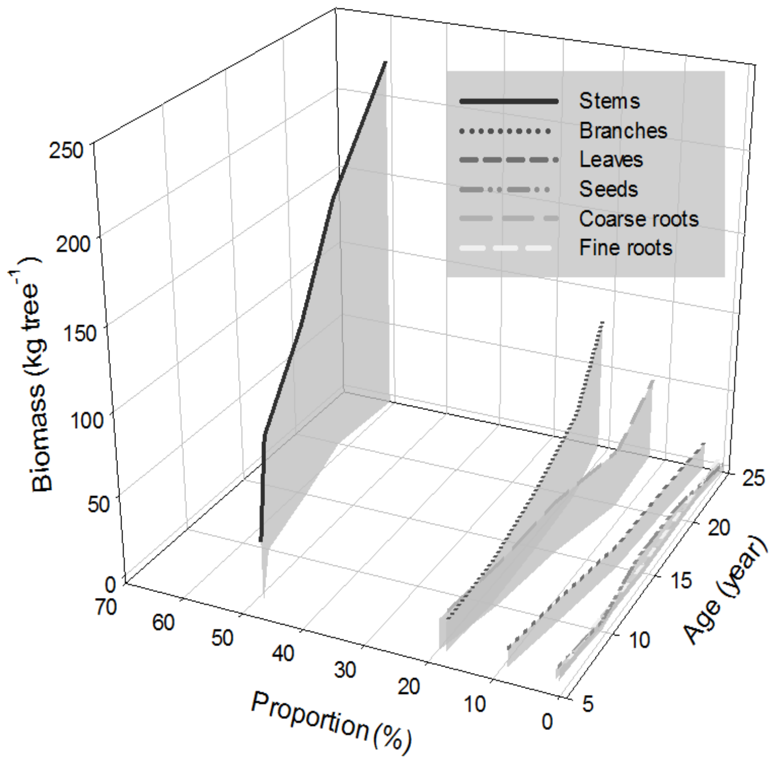

Figure 3.3. The proportion of biomass for the different components of a rubber tree as a percentage of the total tree biomass (*n* = 30, destructively harvested trees).

3.3.2 Wood density and C content of rubber trees

Wood density measured using an increment borer varied from 0.49 to 0.76 g cm^{-3} (mean value 0.64 g cm^{-3}) and increased with *DBH*, while wood density measured in destructively harvested trees (dividing dry mass of stem disk by stem volume) ranged from 0.42 to 0.71 g cm^{-3} (mean value 0.52 g cm^{-3}), with no significant increase with *DBH* (Supplementary Fig. S3.1 a). Carbon concentrations were highest in leaves (48.2%) and fruits (46.7%) and lowest in stems (42.9%). Average whole tree carbon was 43.9% (Supplementary Table S3.4).

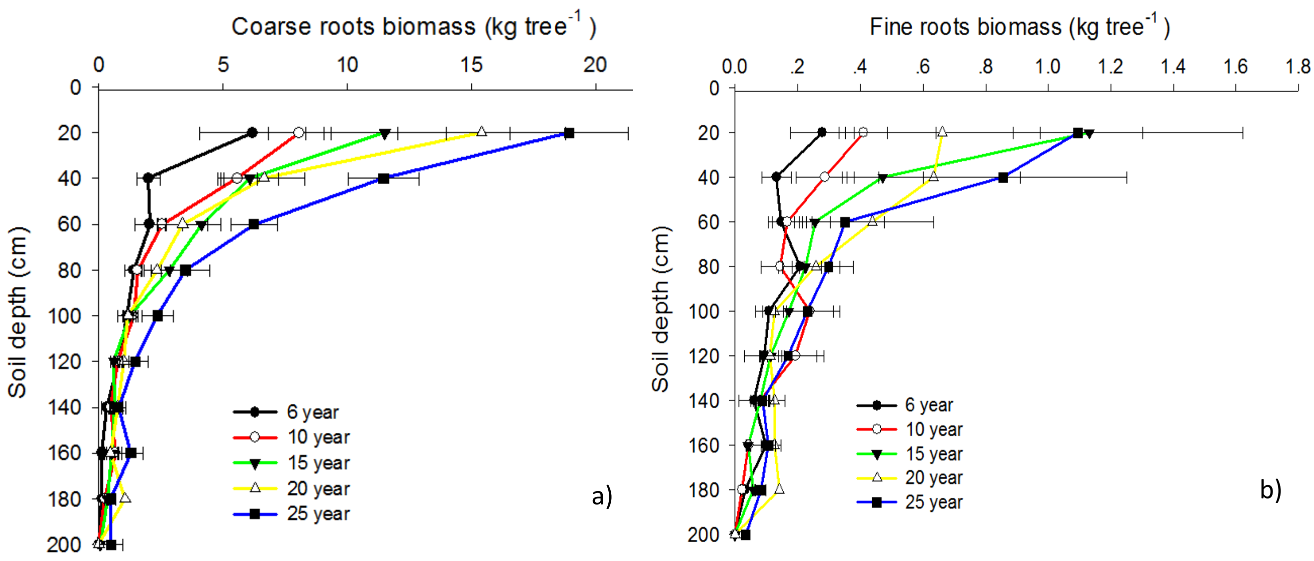

Figure 3.4. Root biomass distribution along various soil depths of a) coarse roots (> 5 mm) and b) fine roots (< 5mm) (*n* =30).

3.3.3 Derivation of allometric equations

Both *AGB* and *BGB* and significantly correlated with *DBH* (Figure 3.5a, supplementary Tables S3.1, S3.2); the proposed allometric equation (Equation 3.2) accounted for 97 and 92% of the variation in AGB and BGB fractions, respectively. Likewise, the regression of stem and branch biomass as a function of *DBH* was significant ($p < 0.001$), with R^2 values of 0.96 and 0.93, respectively. Foliage had a moderate correlation with *DBH*, accounting only for about 80% of the variation in leaf biomass. The diameter distribution of destructively (n = 30) and non-destructively (n = 187) sampled trees was negatively skewed. We sampled rubber trees with *DBH* ranges from 2.7 - 42.8 cm, with the highest frequency (57%) in the 11 – 20 cm range, followed by 0 - 10 cm (24%), 21 - 30 cm (14%), 31 - 40 cm (4%), and 41 - 50 (1%) (Fig. 3.5b). The obtained rubber tree height-diameter relationship (Figure 3.5b) was well described by a log-transformed non-linear regression, similar to the findings of Zhang et al. (2004):

$$\ln(H) = 0.565 + 0.718\ln(DBH) \qquad (3.15)$$

where *H* is tree height and *DBH* is diameter at breast height, with $p < 0.0001$ (RSE = 0.137, R^2 = 0.86). Rubber trees at lower elevations were generally taller and had larger *DBH* values compared to trees at higher elevations within the same age class (Table

3.1).

The optimized parameter values and statistical evaluations of the tested allometric equations are listed in Table 3.2. The equation using only *DBH* as predictive variable (Equation 3.2) gives relative errors of 1.9 and 1.8% for *AGB* and *BGB*, respectively. The added use of tree height data improved model fit (the Adj. R^2 increased from 0.967 to 0.976; the AIC decreased from -32 to -41) and decreased relative error (from 1.9% to 1.2%) in *AGB* prediction. The model with two separate parameters for *DBH* and *H* (Equation 3.4) matched the data better than the integrative model DBH^2H with one parameter (Equation 3.3); the latter decreased model bias and error, but had lower predictive power. Integrating additional explanatory variables, such as wood density or/and crown area, improved predictive ability or led to less bias to a different degree of *AGB* modeling. We found that among models with two predictor variables (*DBH*, *H*), Equation (3.4) was the most suitable model for *AGB* prediction in the landscape of Naban Reserve, while for models with three predictor variables, Equation (3.8) with *DBH*, *H*, and ρ performed best. For *BGB* estimations, considering both model fitness and post-simulation bias, Equation (3.2) was the best for *BGB* modeling by using *DBH* for prediction.

3.3.4 Carbon stock distribution as influenced by landscape and environmental factors

Plot level *AGC* and *BGC* were highly correlated, with a correlation coefficient value of 0.976 (Spearman´s test, see Table 3.3) and depended to a similar extent on environmental variables. The effects of environmental factors on *AGC* were analyzed by using the CART approach (Supplementary Figure S3.2 a, b); the optimum CART tree was constructed using a complexity parameter (CP) value of 0.006 and an x-error value of 0.366 (seven nodes) (Figure 3.6a). The highest *AGC* value was found in old rubber plantations, with lower planting densities (< 570 trees ha^{-1}) than currently employed (i.e. ~650 trees ha^{-1}). The southwestern, western, or northwestern slope aspect had a positive effect on *AGC* accumulation in lowland rubber plantations. The

CART analysis also built the optimum tree for *BGC*, with a CP value of 0.011 and an x-error value of 0.632 (seven nodes) (Figure 3.6b) (for whole tree refer to Supplementary Figure S3.3 a, b). Old rubber plantations cultivated on a gentle slope (< 28°) had the highest *BGC* value. Stand age was the main determining factor for both *AGC* and *BGC*, other identified critical factors were soil clay content, elevation, slope, aspect, MAT, and planting density, with various impacts on *AGC* and *BGC*.

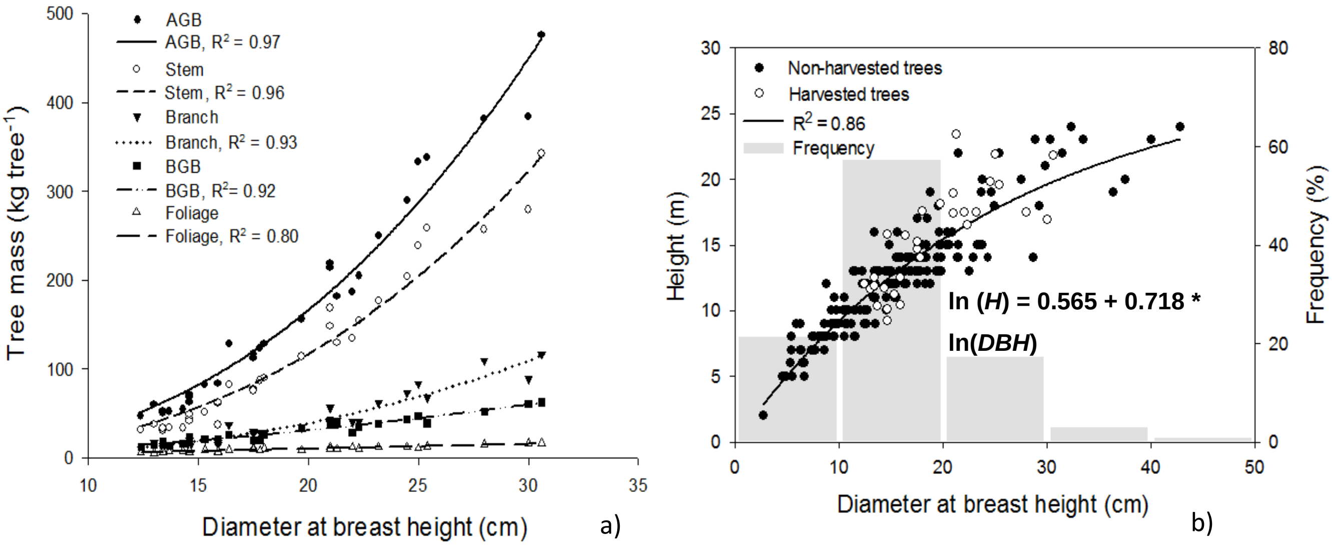

Figure 3.5. Rubber tree biomass and height as dependent on diameter at breast height (DBH): (a) relationship between DBH and different components of rubber tree biomass (lines show biomass from allometric equation Equation 3.2). Aboveground biomass (AGB) includes stems, branches, and foliage, belowground biomass (BGB) includes coarse and fine roots. (b) Tree height vs DBH (Equation 3.15) derived from non-harvested (*n* =187) and destructively harvested (*n* =30) trees. The vertical bars in (b) represent frequencies of sampled trees per diameter class of DBH < 10 cm, 10-20 cm, 20-30 cm, 30-40 cm, and 40-50 cm.

Table 3.2. Regression equations for estimating above ground biomass (AGB) an dbelow ground biomass (BGB) using diameter at breast height (*DBH*) in combi ntion with: height (*H*), wood density (*ρ*), crown area (*CA*) fitted according to r espective models (Equation 3.2-3.10). The allometric coefficients (a, b, c, d, e), residual standard error (RSE), adjusted coefficient of determination (Adj. R^2), Akaike information criterion (AIC), relative error (RE%) for each equation is g iven.

Equation	Ln a	b	c	d	e	RSE	Adj.R^2	AIC	RE%	RMSE
Above ground[a]										
eq (3.2)	-2.996	2.696				0.132	0.967	-32	1.9	26.0
eq (3.3)	-3.209	0.945				0.132	0.967	-32	1.4	22.1
eq (3.4)	-3.183	2.316	0.478			**0.113**	**0.976**	**-41**	**1.2**	**18.2**
eq (3.5)	-1.106	2.213	1.049			0.130	0.968	-33	1.8	22.2
eq (3.6)	-3.107	2.616	0.086			0.133	0.966	-31	1.5	28.0
eq (3.7)	-1.190	2.120	1.068	0.091		0.130	0.968	-31	1.0	23.9
eq (3.8)	-2.027	2.048	0.447	0.635		**0.113**	**0.976**	**-40**	**1.1**	**17.3**
eq (3.9)	-3.326	2.207	0.489	0.109		0.112	0.976	-41	1.3	20.6
eq (3.10)	-2.150	1.933	0.458	0.647	0.110	0.112	0.976	-40	1.3	19.3
Below ground[b]										
eq (3.2)	-1.584	1.668				**0.134**	**0.915**	**-32**	**1.8**	**3.8**
eq (3.3)	-1.653	0.578				0.152	0.891	-24	2.6	4.2
eq (3.4)	-1.626	1.582	0.108			0.136	0.913	-30	1.8	3.7
eq (3.5)	-2.005	1.775	-0.234			0.136	0.912	-30	1.7	3.8
eq (3.6)	-1.467	1.752	-0.091			0.135	0.914	-30	2.0	3.7
eq (3.7)	-1.920	1.869	-0.252	-0.092		0.137	0.911	-28	4.3	3.8
eq (3.8)	-2.263	1.729	0.125	-0.350		0.138	0.911	-28	1.7	3.8
eq (3.9)	-1.512	1.669	0.099	-0.087		0.137	0.912	-29	1.7	3.6
eq (3.10)	-2.165	1.821	0.117	-0.359	-0.088	0.139	0.909	-27	1.7	3.7

[a] The above ground biomass model was based on the sum of three components (stem, branches, foliage) for each tree

[b] The below ground biomass model established based on tree coarse roots and fine roots.

3.4 Discussion

3.4.1 Rubber tree allometry: peculiarities and pitfalls

We set height for DBH measurement at 1.3 m following other studies on rubber biomass estimation (Jia et al., 2006; Tang et al., 2009; Ariff et al., 2017). The DBH measurements at this height are known to be affected by tapping activities because of possible bark deformation (Munasinghe et al., 2014). We could not shift diameter measurement height to higher values (e.g. 1.5 m) as has been done in the study by Munasinghe et al. (2014) because higher tapping frequency for latex collection in China led to tapping panel extension up to heights more than 1.7 m. This holds true for plantations treated with good tapping skills as in our study case in Xishuangbanna,

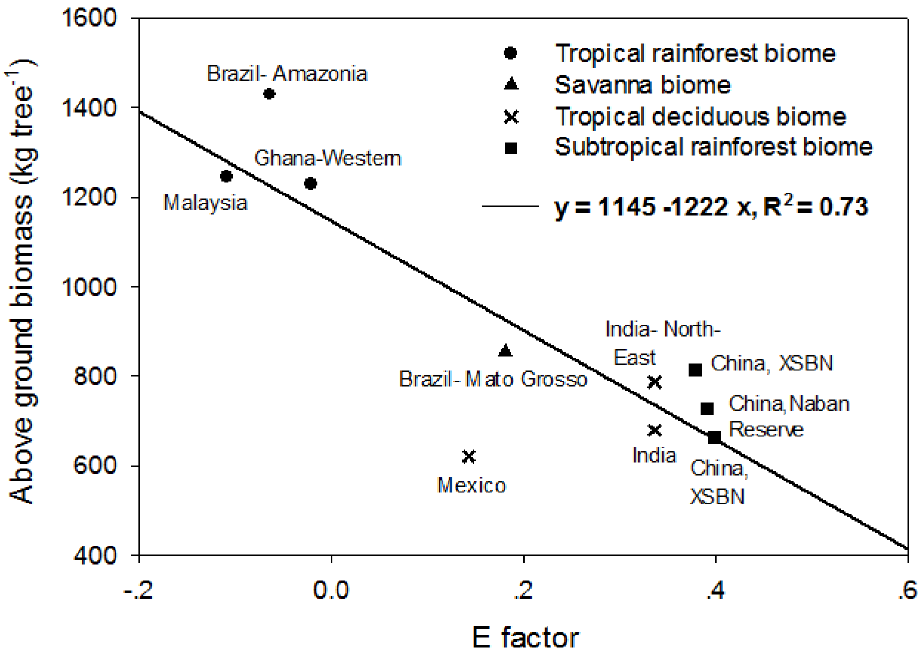

Figure 3.6. Rubber tree AGB distribution in its original growth regions and expansion areas (with various bioclimatic stress factor *E*). Here AGB was estimated based on *DBH* =35 cm, and fitted with existing studies' established allometric equations from Supplementary material Table S3.1.

China. While for plantations with poor tapping quality and associated deformation of regrown bark application of allometric equations derived in our study has to be done with caution. The original format of the allometric equation could be readjusted as $y = a\ (x/x_{ref})^b + \varepsilon$ (Tjeuw et al., 2015), where x stands for *DBH* measured for each tree, and x_{ref} represents a reference diameter equal to the mean of measured sample trees. This modification minimizes the uncertainty in parametrization of allometric equations considering the effect of tree diameters in the sampled dataset, thus stabilizing the b value for a particular a value. We determined the parameters for this equation using our dataset (mean reference diameter of harvested trees was 19 cm):

$$AGB = 141(DBH/19)^{2.6957} \tag{3.16}$$

with RSE = 0.132, Adj. R^2 = 0.967, AIC = -32, RE% = 0.5, RMSE = 24.5 kg $tree^{-1}$; while

$$BGB = 28(DBH/19)^{1.667} \tag{3.17}$$

with RSE = 0.134, Adj. R^2 = 0.915, AIC = -32, RE% = 0.6, RMSE = 3.7 kg $tree^{-1}$.

Table 3.3. Correlation between AGC, BGC (Mg C ha^{-1}) and environmental variables, tested by Spearman Correlation analysis.

Variables	MAP	MAT	Elevation	Age	Slope	Aspect	Density	Sand	Clay	Silt	C/N	SOC	AGC	BGC
MAP	**1**													
MAT	**-0.998****	**1**												
Elevation	**0.911****	**-0.912****	**1**											
Age	-0.271	0.262	-0.215	**1**										
Slope	-0.065	0.060	-0.111	-0.069	**1**									
Aspect	0.106	-0.112	0.122	0.256	-0.011	**1**								
Density	0.065	-0.048	0.073	-0.337	-0.003	0.005	**1**							
Sand	0.135	-0.132	0.160	**-0.456***	0.351	-0.103	0.048	**1**						
Clay	-0.005	-0.010	-0.047	**0.674****	-0.188	0.169	-0.194	**-0.827****	**1**					
Silt	0.135	-0.132	0.160	**-0.456***	0.351	-0.103	0.048	**1.000****	**-0.827****	**1**				
C/N	**0.399***	**-0.394***	**0.540****	0.190	-0.177	-0.128	-0.118	-0.139	0.252	-0.139	**1**			
SOC	0.194	-0.192	0.323	-0.105	-0.021	0.090	-0.204	0.206	-0.220	0.206	**0.389***	**1**		
AGC	**-0.449***	**0.446***	**-0.429***	**0.942****	-0.064	0.263	-0.283	**-0.494***	**0.631****	**-0.494***	0.017	-0.264	**1**	
BGC	**-0.480***	**0.481***	**-0.447***	**0.903****	-0.105	0.322	-0.211	**-0.460***	**0.580****	**-0.460***	-0.059	-0.269	**0.976****	**1**

Note: ** correlation is significant at the 0.01 level, * correlation is significant at the 0.05 level (2 tailed). MAP (mean annual precipitation, mm); MAT (mean annual temperature, °C); Elevation (meter.a.s.l); Age (plantation stand age, year); Slope (°); Aspect (°); Density (plantation planting density, trees ha^{-1}); Sand (soil sand concentration percentage, %); Clay (soil clay concentration percentage, %); Silt (soil silt concentration percentage, %); C/N (dimensionless unit); SOC (soil organic carbon, Mg ha^{-1}); AGC (above ground carbon, Mg ha^{-1}); BGC (below ground carbon, Mg ha^{-1}).

The *b* value in the modified equations 3.16 and 3.17 is the same as in Equation 3.2 for both *AGB* and *BGB* (Table 3.2). This means that allometric equations with *b* values derived in our study should be appropriate for application in other studies with similar environmental conditions. The usage of the reformulated allometric model (i.e. Equation 3.16 and 3.17) decreased relative errors (RE% and RMSE), so this approach could be advisable for further studies.

The parameter *b* in allometric equation (e.g. Equation 3.1 or Equation 3.2) can be estimated from the site-specific relationship between tree height and *DBH* (Ketterings et al., 2001). Following this approach, we obtained a *b* value (b= 2+c = 2.718) using parameter *c* from Equation 3.15, which is the linearized form of Eq.8 in Ketterings et al. (2001). At the same time, the *b* value estimated for *AGB* in the present study by means of parametrization of Equation 3.2 was 2.696. This difference means that rubber trees in our study had slightly lower *DBH* increments per height unit as compared to that found in the study of Ketterings et al. (2001). The application of the general allometric equation with parameter *b* derived from *DBH* to height ratio and parameter *a* derived from measured wood density and constant factor 0.11, i.e. following Equation 3.11 in Ketterings et al (2011), would lead to a 27% overestimation of *AGB* compared to the that using our Equation 3.2 calibrated with the help of the destructive method. As the approach of Ketterings et al (2011) was calibrated against mixed secondary forests, it requires further modification when applied for managed rubber plantation to simulate biomass. Here the relationship between tree height and *DBH* is affected by tapping activities decreasing radial stem growth rate of tapped rubber trees as compared with untapped trees (Silpi et al., 2006). Thus, under intensive tapping management, rubber plantations show constrained diameter increment when compared with forest. Therefore, the non-destructive approach proposed by Ketterings et al. (2001) for forest biomass estimation should be re-calibrated for rubber plantations.

An alternative non-destructive method for allometric equations establishment is the functional branches analysis (FBA). This approach requires quantitative information gathered at each branching point, namely, length-diameter relationships, the link taper, wood density and distribution of scaling factor *p* and allocation parameter *q* (for details refer to MacFarlane et al., 2014). Although, this approach has shown promising potential for non-destructive estimates of tree biomass, it requires more parameters and still needs to be tested for rubber in future studies.

Allometric equations based on *DBH* can be also improved by adding height, wood density, or crown area (Ketterings et al., 2001; Chave et al., 2005). However, the effects of adding these tree parameters differ between various studies. According to our results, adding tree height with its own scaling parameter can considerably improve rubber tree *AGB* prediction, while adding integrative tree height and *DBH* (DBH^2H) was less effective. Adding height as integrative variable DBH^2H was also ineffective in other studies (Jia et al., 2006; Tang et al., 2009). Besides, allometric relationships between height and components of biomass might be affected by management activities, such as regularly pruning the top of rubber trees to avoid wind damage in some regions (e.g. India or Hainan in China) (Sone et al., 2009). Crown area did not significantly contribute towards model improvement in the current study, possibly because of the averaging of tree crown effects on biomass for different clone types during derivation of mixed clone allometric equations. Furthermore, distance between rows in the plantation varied within the landscape and affected individual tree crown shape; therefore, in averaged allometric equations, crown shape was not a significant factor. Although previous studies have suggested to establish clone-specific equations to avoid biomass estimation errors (Khun et al., 2008; Sone et al., 2009), Shorrocks et al. (1965) showed that allometric relationships did not differ significantly among rubber tree clones in Malaysia. Additionally, a general equation applicable for different clones could be useful for landscape-level assessments of biomass (e.g. Chaudhuri et al., 1995; Wauters et al., 2008), where an application of clone-specific equations is not possible because of a lack of clone distribution information.

Wood density varies with clone type, planting density, and growth conditions. The wood density found in our study fall into the range (0.39 - 0.67 g cm^{-3}) reported by others (Naji et al., 2011; Chukwuemeka, 2016). Adding wood density to *DBH* and *H* did not significantly improve model accuracy when compared with the model containing only *DBH* and *H* (similar AIC, RE% and RMSE), and the uncertainty due to variation in measured wood density might be one reason. Average wood density measured using harvested trees (0.52 g cm^{-3}) was independent from *DBH* and close to the value provided in the wood density database of the World Agroforestry Centre (0.53 g cm^{-3}) (http://db.worldagroforestry.org/wd). However, wood density obtained with the increment borer (0.64 g cm^{-3}) had a significant linear relationship with *DBH*. In practice, it was difficult to sample wood through the entire trunk with the stem borer as the samples were always shorter than 30 cm. Thus, the under-sampling of wood in outer parts of trunks of large trees (on the side opposite to the first bore opening and apart from the center of the tree) produced a systematic error and further affected average wood density (Supplementary Figure S3.1 b). The high wood density variations in radical direction of stem cross-section (Knapic et al., 2008) could be the reason for the observed bias. In future applications of this method, it is advisable to sample all parts of the trunk representative for trees of different sizes. Another reason for the weak effect of wood density on tree biomass in the allometric equations might be that this parameter in rubber monocultures was relatively constant opposed to multi-species forests (Baker et al., 2004; Chave et al., 2006).

3.4.2 Comparison with existing locally developed allometric equations: sources of uncertainties

Published allometric equations showed greater variability in trees with larger *DBH* values (Figure 3.7). Largest discrepancies were observed between the models of Schroth et al. (2002) and Rojo-Martinez et al. (2005). The observed *AGB* values in the current study fell within modeled curves from Chaudhuri et al. (1995) and Dey et al. (1996) established in India, Rojo-Martinez et al. (2005) in Mexico, Jia et al. (2006) and Tang et al. (2009) in Xishuangbanna of China, as well as Wauters et al. (2008) in Mato Grosso, Brazil. Thus, we performed a detailed error distribution comparison for these equations in each diameter class, together with the two best *AGB* equations established in the current study (Figure 3.8). Most models over-predicted *AGB* (1.1-46.4%), except the models of Rojo-Martinez et al. (2005) and Tang et al. (2009), which under-predicted *AGB* (0.4-13.6%). However, the best equations developed in the current study (Equation 3.4 and Equation 3.8) displayed stable relative error distributions across different *DBH* groups and smaller RE% and RMSE than most other models. Furthermore, some models developed in the same region as our study were relatively robust in the prediction of tree biomass based on *DBH* only.

Nevertheless, the model of Jia et al. (2006) had higher simulation errors compared to our models, most likely as it was calibrated on plantations with a *DBH* range covering only up to 20 cm (14-year-old rubber trees). Therefore, the authors´ equation should not be applied to older plantations. The models from Tang et al. (2009) yielded smaller relative error as ours, possibly because their calibration dataset covered tree stand ages from 4 to 47 years, although their study did not consider highland rubber plantations. The goodness of fit of Tang’s model to our data set indicates that stand age has higher predictive power than elevation.

Compared with *AGB* estimations, up to date, only a few studies have estimated belowground rubber tree biomass in South East Asia. Hence, detailed root profiles are still poorly understood, resulting in large uncertainties (Yuen et al., 2013; Blagodatsky et al., 2016; Yuen et al., 2016). Even fewer studies have been investigating ecosystem functions of deep roots (Maeght et al., 2013; Laclau et al., 2013), which can reach 2.4 m and 9 m length (taproot and lateral roots, respectively) already for 7 - 8 years old trees (Priyadarshan, 2017). Therefore, even with low root densities over considerable soil depths, deep roots could still pose impacts on belowground carbon stocks. Thus, we probably underestimated root biomass compared to actual values over whole root profile with slight bias due to limited sampling of inter-row space and omitting deep roots.

Several allometric equations for *BGB* were tested against our data on root biomass to 2 m depth (Figure 3.9). Except the model by Wauters et al. (2008), which underestimates *BGB* by 1.8%, all other models resulted in overestimation, with values ranging from 1.8 to 41.3% (Figure 3.10). All equations showed overestimation of *BGB* in *DBH* groups larger than 25 cm. Equation (3.2), developed in the current study, and the equation from Wauters et al. (2008) showed the smallest bias for *BGB* simulations; however, the allometric equations developed in the present study had a better prediction for trees with small or large diameters (lower % RE and RMSE). This could be explained by the differences in tree age distribution in the compared studies. Allometric equations derived for Western Ghana were based on sampled trees of 2 - 17 years of age, while other models were based on data covering older trees, such as in Wauters et al. (2008) in Mato Grosso, Brazil (15 - 26 years), Tang et al. (2009) in Xishuangbanna (7 - 47 years), and Yuen et al. (2013) with even broader age

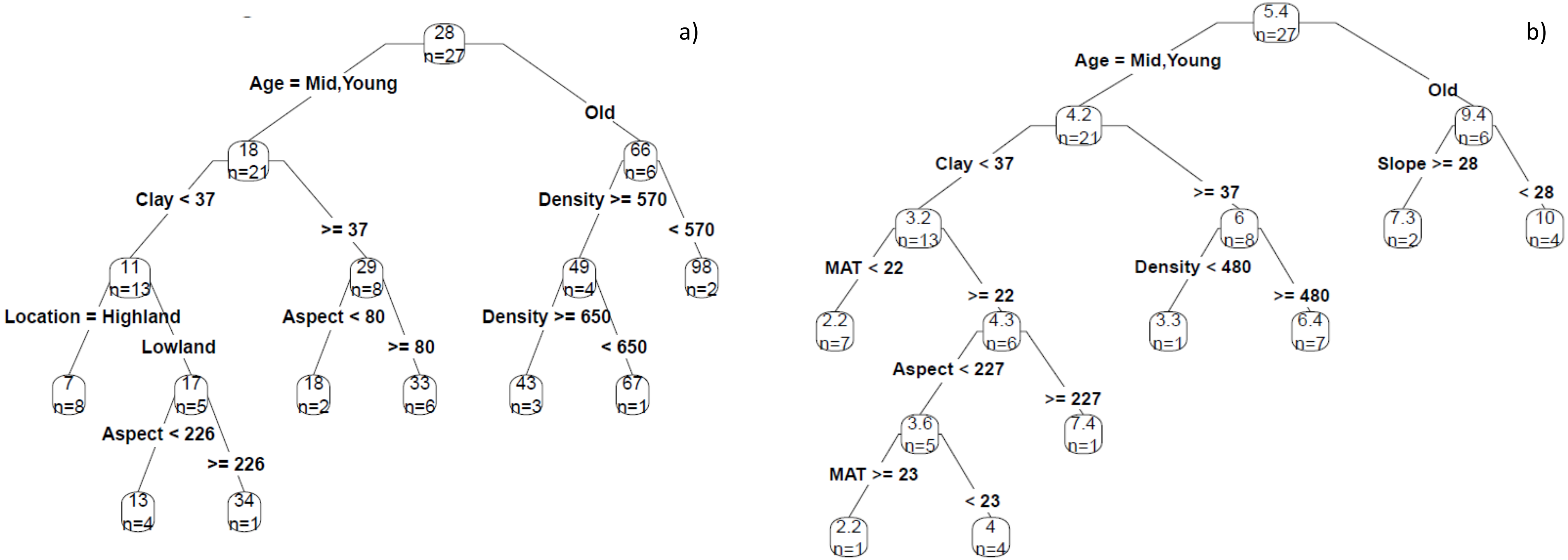

Figure 3.7. Environmental factors effects on above ground and below ground C stocks. CART analysis of AGC (a) and BGC (b). For each segmentation, the segregating variables and thresholds value was displayed. The average value of AGC or BGC (Mg ha^{-1}) and number of observations (*n*) was displayed in corresponding node. Here Age is rubber plantation stand age, which divided into three groups (young, mid-aged and old, unit years, refer to Table 1); clay is soil clay content (%), location is referring to elevation range (lowland and highland, unit meter, refer to Table 1); density is planting density (trees ha^{-1}); aspect (°); slope (°); MAT is mean annual temperature (°C).

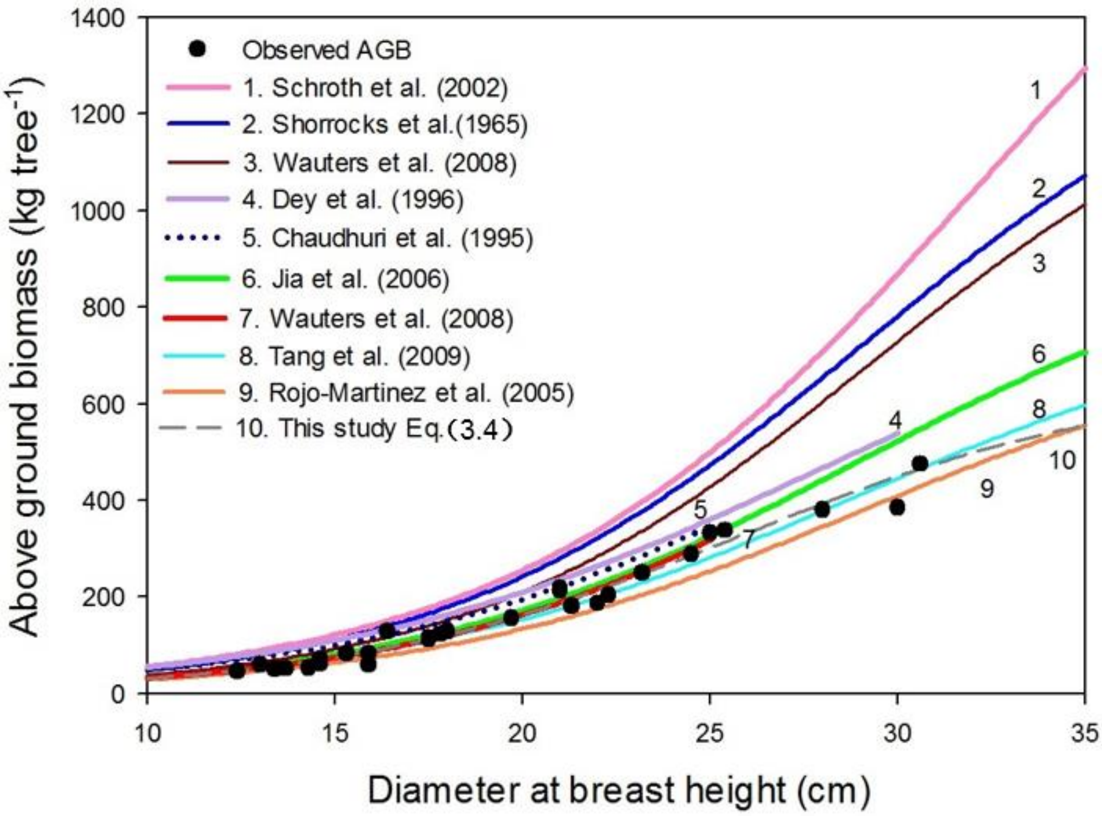

Figure 3.8. Allometric equations linking aboveground biomass of rubber tree and diameter at breast height established for different regions, see also supplementary material Table S1. Here the largest diameter at breast height of some curves was set differently to make better illustration and avoid overlay.

groups from a global dataset. The differences in tree age of sampled datasets could partly explain differences between our and other models. The higher planting density and tapping frequency can negatively influence root development in our mountainous study site, so that most of other models overestimated measured *BGB*. Other studies in Xishuangbanna (Tang et al., 2008) were completed for rubber trees grown in climatically more suitable habitats (< 640 m), thus their equations could result in overestimation if used in areas with higher elevation. This also holds true for other rubber cultivation countries (and for *AGB*), as indicated in Figures 3.9 and 3.10. Global root-to-shoot ratio (R/S) could not represent regional site-specific tree growth characteristics, thus it is unsurprising to observe large RMSE error of estimations if this kind of model is validated against a regional dataset. The uncertainty increases if tree age is incorrectly estimated or trees of the same age, but grown in different regions, are compared. For instance, we fitted Equation 3.5 from Blagodatsky et al.

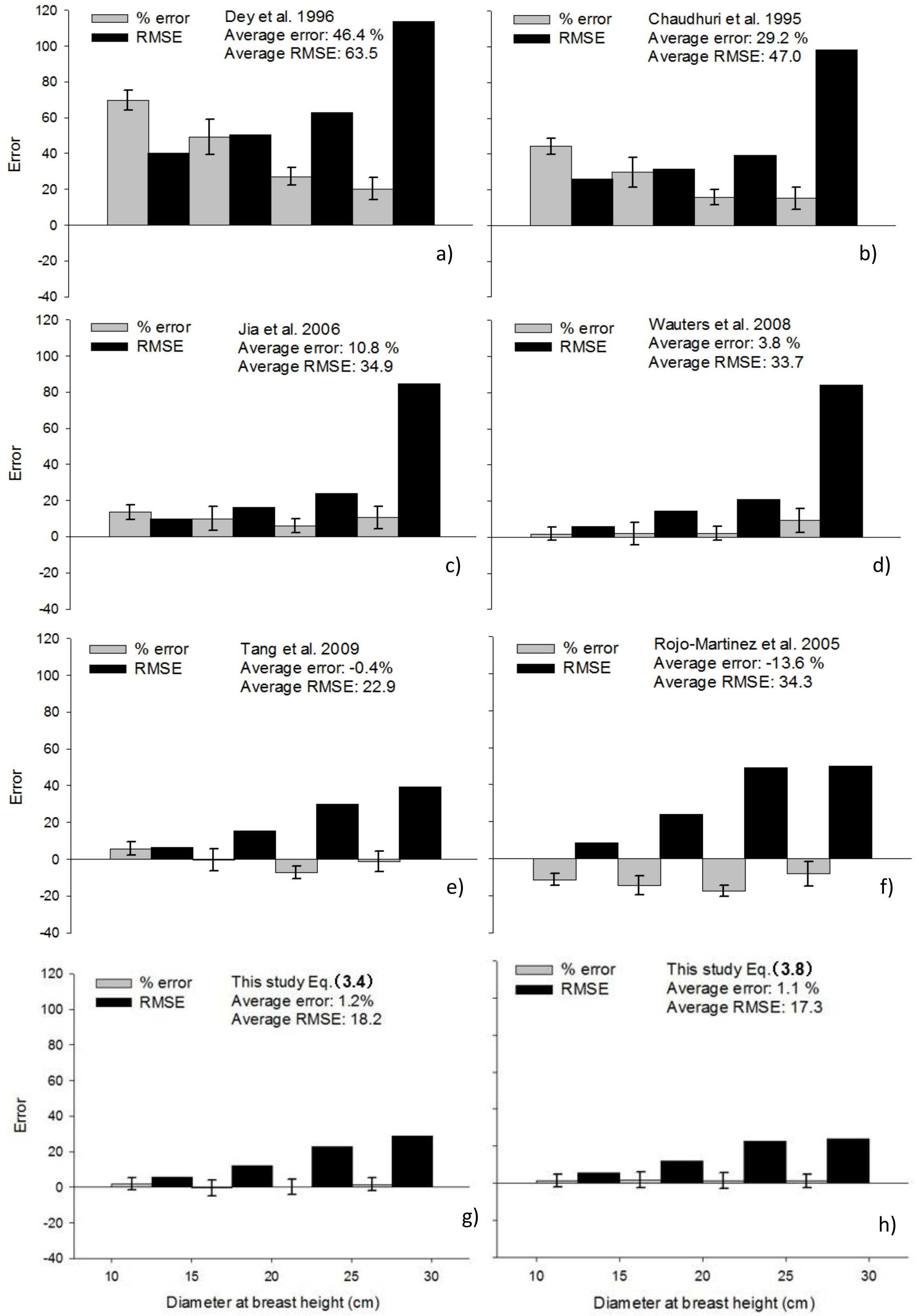

Figure 3.9. Disaggregation of the relative error by tree size for the published equations for above ground biomass (a-f), corresponding to the equations in Supplementary material Table S3.1 (Equations No S3.4-S3.9) in the text and the equation proposed in this study (g-h).

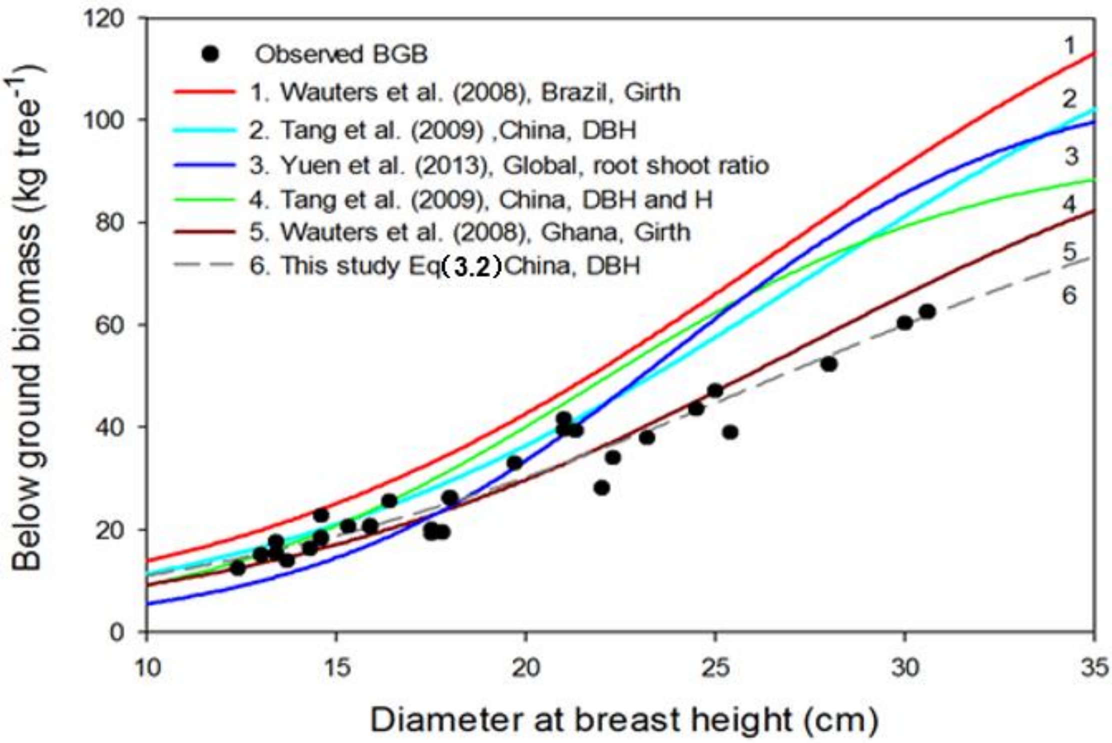

Figure 3.10. Belowground biomass estimated by diameter at breast height (DBH) or root shoot ratio. Black dots present observed data (destructive sampling); relationships were modeled according to published equations (see Supplementary material Table S3.2).

(2016) with our harvested tree age and measured *BGB*, obtaining a 10% relative error. This was the result from the inclusion of high elevation tree samples in the current study. Therefore, the allometric equation linking *DBH* with *BGB* calibrated against a local dataset matched better measured biomass and therefore was applied in our case for estimation of R/S.

We compared the estimations of plot-level carbon stocks from the same 25 rubber plantations evaluated by Yang et al. (2016) with those found in the current study. The average *AG*C in the previous evaluation was 37 Mg C ha^{-1}, while it was 25 Mg C ha^{-1} according to our new models. According to the previous work, *BGC* was 7 Mg C ha^{-1}, while our updated results showed an average *BGC* of 5 Mg C ha^{-1}. Relative overestimation was 30% and 29% for *AGC* and *BGC*, respectively. The two approaches differed in their allometric equations for biomass estimation and in values of C concentration taken for biomass to carbon conversion. The C concentration found in the current study (0.44) was similar to that obtained by Chantuma et al. (2012), but lower than in publications of Saengruksawong et al. (2012) (0.57) and

Wauters et al. (2008) (0.51). If studies uses the biomass to C conversion factor 0.5, as recommended by the IPCC, this results in a relative 12% overestimation of total biomass C ((50-44)/50*100). In this way, we recommend using C concentration values developed in a similar regional environment for biomass to carbon conversion. Furthermore, for a successful REDD+ project at landscape level, assessment of uncertainties for aboveground and belowground carbon stocks of different land use types is a precondition. Carbon emission information could be derived from time-averaged carbon stock values and guiding management of local decision makers (Cowie et al., 2007; Hairiah et al., 2011; Yang et al., 2016). Additionally, taking into account estimations of uncertainty of various spatial and temporal resolutions of land use change mapping is essential to fairly assess the efficiency for emission reduction under a REDD+ mechanism (Lusiana et al., 2014).

3.4.3 Bioclimatic and management factors in allometric equations for biomass estimation in rubber cultivation regions

At present, for regions where no allometric equations for rubber are available, the general equations for tropical forests are applied for rubber tree biomass estimations (Corpuz et al., 2014). However, the suitability of these models has not been verified and they could potentially introduce substantial errors. In order to evaluate the impact of local environmental conditions on rubber tree biomass, we plotted the estimated *AGB* values of various studies (with *DBH* = 35 cm) against the *E* factor in Figure 3.11 (see also section 3.2.2.2). In this case *E* values represent the climatic gradient for rubber planting regions increasing from -0.109 to 0.397 in the order tropical rainforest biome > savanna biome > tropical deciduous biome > subtropical rainforest biome. Original rubber growth regions had negative *E* values, while regions with introduced rubber trees showed positive *E* values, reflecting a higher level of environmental stress and confirming that rubber was frequently planted under sub-optimal conditions (Ahrends et al., 2015). Figure 3.11 clearly demonstrates the positive impact of better climatic conditions on rubber tree biomass development.

In the context of the current study, application of the pan-tropical forest diameter-height model (Equation 6a and Equation 7 from Chave et al., 2015) underestimated tree height, with a relative error of 20% (RMSE = 4.8 m); however, *AGB* was only slightly overestimated, with a relative error of 5% (RMSE = 36 kg tree^{-1}) (Supplementary Figure S3.4 a, b). The discrepancy between pan-tropical *DBH*-height model predictions and measured tree height was probably caused by the detrimental effect of rubber tree tapping on radial growth of tree stem (Silpi et al., 2006), which is not the case for tropical trees used for calibration of Equation 6a by Chave et al. (2015). This confirms our findings discussed in section 3.4.1.

The value of the *E*-factor in the allometric equation derived for tropical forests and used for the correction of local climate impact on photosynthetic activities and biomass partitioning may differ for rubber trees due its high drought tolerance (Tan et al., 2011; Wang et al., 2014). Nevertheless, the general pan-tropical model by Chave et al. (2015) (see Equation 7 in the cited paper) could provide a better estimation of *AGB* if a bioclimatic factor *E* and regionally derived wood density values were added in the equation.

Therefore, we parametrized this model using our data, yielding the following equation:

$$AGB_{est} = \exp\left(-2.284 - 0.625E + 0.867\ln(\rho) + 3.029\ln(DBH) - 0.122(\ln(DBH))^2\right) \quad (3.18)$$

where E = 0.391, $P < 0.0001$, RSE = 0.134, Adj R^2 = 0.966, AIC = -28.

The performance of Equation 3.18 was clearly lower than that of other models established in the current study (Table 3.2), as observed from a comparison of RSE, Adj. R^2, and AIC. A narrow range of environmental stress factor *E* (0.36-0.40) along the sampled plots in our landscape did impede improved biomass prediction with the proposed equation. However, the strength of Equation 3.18 is in its transferability to other regions. We accounted for local conditions by introducing the *E* factor so that, if data on wood density is available, this ‘rubber adjusted’ equation can potentially be applied for non-destructive *AGB* estimation across larger spatial scales.

Planting density is an important factor affecting individual tree growth performance through the light captured by plants. Naji et al. (2012) reported decreased diameter at breast height and basal area of rubber trees with increasing planting density. Our analysis (Figure 3.6a and 3.6b) confirmed the importance of planting density in determining regional above- and belowground carbon stock distributions. Therefore, the bioclimatic stress factor *E* needs to be added in allometric equations for evaluation of pan-tropical rubber-based plantation systems, but those equations should still

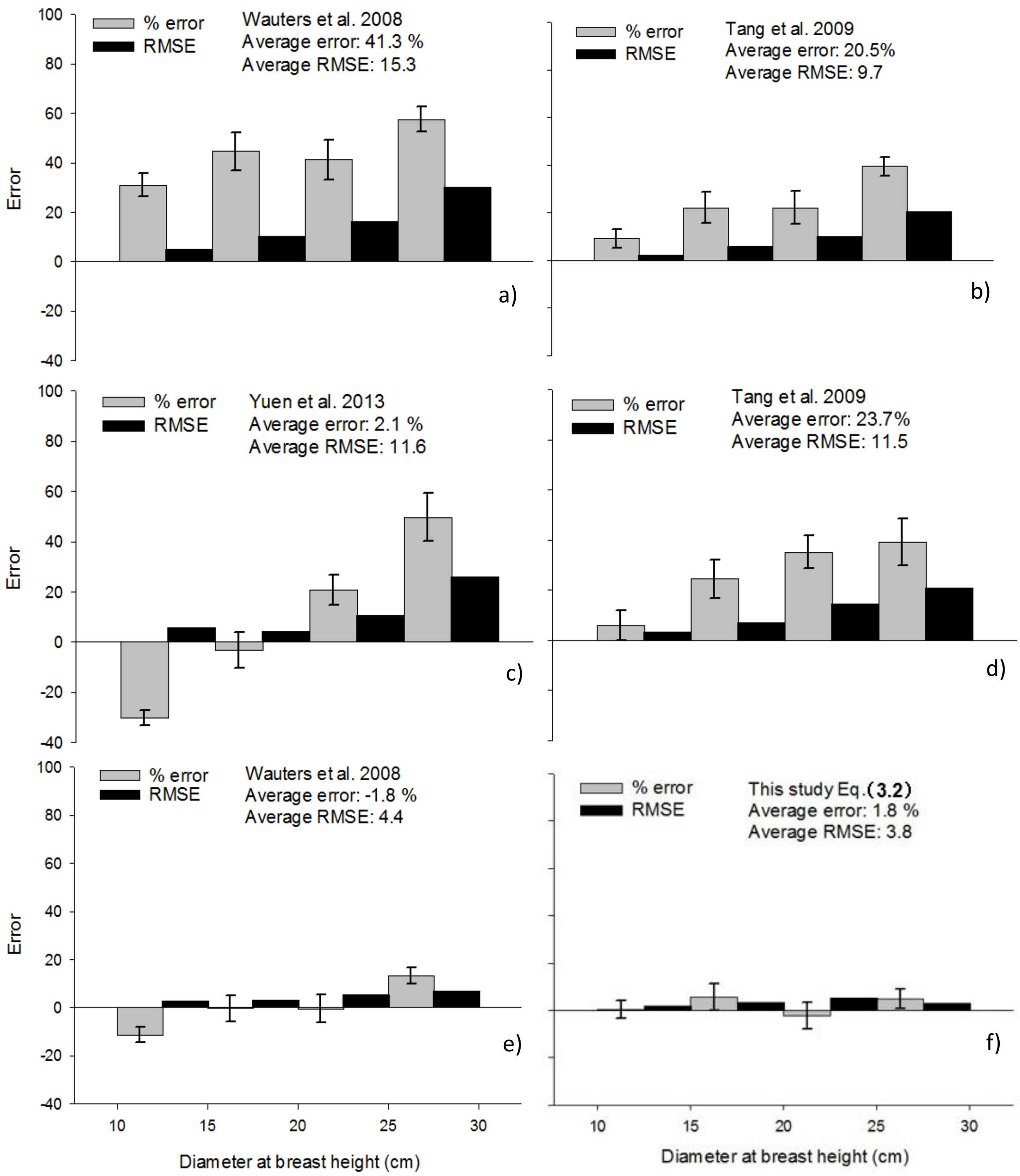

Figure 3.11. Disaggregation of the relative error by tree size for the published equations for below ground biomass (a-e), corresponding to the equations in Supplementary material Table S3.2 (Equations No S3.1-S3.5) in the text and the equation proposed in this study (f).

consider regional management strategies for achieving reliable biomass evaluations. Rubber plantations in the studied region differ from those in regions with climatic conditions more suitable for rubber growth, i.e. in Southern Thailand, Indonesia and Malaysia. However, large territories in Montane Mainland Southeast Asia (Vietnam, Northern Thailand, Xishuangbanna in China and other regions) are now occupied by rubber plantations growing in marginal conditions (Xu et al., 2013; Fox et al., 2014). Considering the rubber growth in these marginal conditions is still insufficiently investigated, the results of the current study could provide reference for other countries. Our results are consistent with findings of Wauters et al. (2008), who described the faster development of rubber *AGB* in a tropical forest biome, while in tropical semi-deciduous, and savanna biomes, trees showed slower accumulation of *AGB*. This large-scale biome effect was more obvious than the regional site-specific environmental impacts. Moreover, Yang et al. (2016) also reported similar effects of biome on time-averaged C stock values.

3.4.4 Influence of environmental conditions on landscape level carbon distribution

In the current study, CART analysis reflects an integrative effect of environmental factors on per plot carbon stocks (Figure 3.6). As expected, rubber plantation stand age was the dominant factor affecting carbon stock distribution at the landscape level. Therefore, many authors (Wauters et al., 2008; Tang et al., 2009; Song and Zhang., 2010; Petsri et al., 2013; Song et al., 2014; Yang et al., 2016) used stand age as a predictor of carbon stock. Mapping of rubber plantation age at regional scale, e.g. using free available Landsat TM & ETM time series dataset and pixel-based image compositing (Beckschäfer, 2017), can help in upscaling of the C stock estimates from plot to landscape level. Similar to our study, Samarappuli (2000) found that rubber has optimum conditions for growth and production of latex on soils with sufficient clay content (minimum 35%). Rubber plantations are generally distributed on clayey and acidic soils within the Naban Reserve. The positive correlation between clay content and rubber plantation stand age probably reflect the fact that the older rubber plantations were established on more fertile and suitable soils, while newly cultivated rubber plantations face challenge to find similar soil conditions. The most suitable microclimate for rubber tree growth and latex flow is a southeasterly aspect in our region where sunshine is most direct, with high humidity and low temperature in the early morning (Zeng and Yanping, 2004). In the current study, both *AGC* and *BGC* did not show significant correlations with aspect, while in the CART analysis aspect was identified as an important factor, suggesting that interactions with other environmental factors enhance the effect of aspect.

Planting density in rubber plantations varies from 206 to 667 trees ha^{-1} (Schroth et al., 2002; Jia et al., 2006; Wauters et al., 2008; Tang et al., 2009). We found even higher densities in the Naban Reserve: 360-900 trees ha^{-1}, the latter particularly associated with higher elevations. The CART analysis showed the threshold value of planting density for *AGC* (around 570 trees ha^{-1}) for old rubber trees; beyond this value, negative effects on tree carbon stocks can be expected. For young and mid-aged rubber trees, the impacts of planting density were not obvious. However, for *BGC*, a threshold for planting density was not detected (*BGC* still increases with higher planting density in young and mid-aged rubber plantations), suggesting that belowground components of rubber trees are not impacted by higher planting density. Besides, other critical factors such as elevation, slope, and MAT were also identified. Areas most suitable for tree biomass development were below 800 m (Yang et al., 2016), while areas most suitable for high profit rubber plantations were below 900 m (Yi et al., 2014b). Rubber plantations of the same age contained less carbon in unsuitable areas with lower temperatures (at higher elevation) and dryer conditions. The same rule holds true for landscape-level time-averaged C stocks (Blagodatsky et al., 2016; Yang et al., 2016). The management factor, such as planting density in the present study, has to be considered in future carbon stock estimation studies. Effective strategies to optimize landscape carbon sequestration potential can be developed using tools proposed in this study.

3.5 Conclusions

The allometric biomass models developed here are valid for rubber plantations with *DBH* values ranging from 12 to 31 cm (girth 38 to 97 cm), and the height models can be applied to trees with *DBH* values from 3 to 43 cm (girth 9 to 135 cm). These models are applicable for mixed clone types of rubber plantations in the mountainous landscape of Xishuangbanna, China. Our analysis of the impact of environmental factors on carbon stock distribution had the potential constraint for detecting climatic effects due to the relatively small sampling area. The *AGB* models had higher accuracies after introducing the tree height as additional parameter, while using *DBH* alone can already provide a robust *BGB* estimation. Most existing rubber tree allometric equations were constrained by their site-specific conditions, which impede their further application in other regions; this was also the case for the current study. Therefore, we tested a recently published pan-tropical forest allometric equation, which includes as driving variables an environmental stress factor *E* and wood density. Despite the goodness of fit for the pan-tropical model for rubber was less than for locally validated allometric models (Equation 3.2 and 3.4), it has a good perspective for application in other regions, if destructive biomass measurements are impossible. Rubber plantations are intensively managed tree systems, and rubber tree development is influenced, inter alia, by tapping activities (Silpi et al., 2006). We found that general allometric equations proposed for tropical forests (e.g. by Ketterings et al., 2001 or by Chave et al., 2015) were not appropriate for rubber plantation. The relationships between *DBH* and height and between *DBH* and biomass were influenced by tapping (see also Annamalainathan et al., 2013), therefore biomass and C stock calculation for rubber has to be done using species specific allometric equations, as for example proposed in current study.

To understand landscape-level determining factors for rubber tree carbon stock distribution, the classification and regression tree (CART) approach was applied. The most critical factors for both *AGC* and *BGC* were stand age, soil clay content, aspect, and planting density. The high-density design adopted by local farmers has a negative effect on aboveground carbon stock of old rubber plantations. Therefore, in contrast to natural forest biomass estimation, we advise to consider the bioclimatic and regional management factors (e.g. tapping frequency, planting density) for building predictive and widely applicable biomass models for pan-tropical rubber-based systems. Our results provide a reference for conducting reliable carbon accounting and for adapting rubber-based systems to climatic changes.

3.6 Supplement

Table S3.1. Regional allometric equations linking aboveground biomass of rubber tree and diameter at breast height. BA, G and D stand for basal area, girth and diameter at breast height. Bioclimatic factor *E* was extracted from the gridded layer at 2.5 arc minute resolution from http://chave.ups-tlse.fr/pantropical_allometry.htm (Chave et al., 2015).

No.	Allometric equation	Region	*E* factor	Source
S3.1	$y=-3.84+0.528*BA+0.001*BA^2$	Brazil- Amazonia	-0.064	Schroth et al. (2002)
S3.2	$y=0.002604*G^{2.7826}$	Malaysia	-0.109	Shorrocks et al. (1965)
S3.3	$y=exp(-7.26+2.904*ln(G))/0.487$	Ghana-Western	-0.021	Wauters et al. (2008)
S3.4	$y=0.0202*G^{2.249}$	India-North-East	0.336	Dey et al. (1996)
S3.5	$y=0.002278\ G^{2.682}$	India	0.336	Chaudhuri et al. (1995)
S3.6	$y=0.0681*D^{2.6409}$	China- XSBN[a]	0.303	Jia et al. (2006)
S3.7	$y=exp(-6.748+2.723*ln(G))/0.487$	Brazil- Mato Grosso	0.181	Wauters et al. (2008)
S3.8	$y= y_{sterm} + y_{branch} + y_{leave}$, $y_{sterm}=0.05*D^{2.596}$, $y_{branch}=0.015*D^{2.563}$, $y_{leave}=0.007*D^{2.215}$	China- XSBN	0.398	Tang et al. (2009)
S3.9	$\ln y=-3.1426+2.69273*\ln D$	México	0.143	Rojo-Martinez et al. (2005)
S3.10	$y= 0.05*D^{2.696}$	China- Naban Reserve	0.391	Current study

[a] XSBN Stands for Xishuangbanna, China.

Table S3.2. Regional allometric equations linking belowground biomass of rubber tree and diameter at breast height.

No.	**Allometric equation**	**Region**	**Source**
S3.1	$y=exp(-4.284+1.792*ln(G)/0.487$	Brazil- Mato Grosso	Wauters et al. (2008)
S3.2	$y=0.108D^{1.948}$	China- XSBN	Tang et al. (2009)
S3.3	root shoot ratio (0.2)	Global	Yuen et al. (2013)
S3.4	$y= 0.0563(D^2H)^{0.7439}$	China- XSBN	Tang et al. (2009)
S3.5	$y=exp(-4.996+1.872*ln(G)/0.487$	Ghana-Western	Wauters et al. (2008)
S3.6	$y=0.205D^{1.668}$	China- Naban Reserve	Current study

Table S3.3. Biomass partitioning (Mean ± S.E., kg $tree^{-1}$) in different tree components at different tree ages (*n* =30, six trees were sampled for each age class).

Components	**6 years**	**10 years**	**15 years**	**20 years**	**25 years**
Stems	34.0 ± 1.2 (48%)	66.5 ± 15.8 (55%)	104.7 ± 20.8 (58%)	156.3 ± 37.4 (62%)	222.0 ± 31.7 (61%)
Branches	13.2 ± 1.3 (19%)	21.6 ± 4.5 (18%)	33.0 ± 6.4 (18%)	48.6 ± 9.9 (19%)	79.8 ± 12.5 (22%)
Leaves	6.6 ± 0.5 (9%)	8.9 ± 0.9 (7%)	9.1 ± 0.8 (5%)	11.1 ± 1.2 (4%)	12.3 ± 1.2 (3%)
Seeds	1.4 ± 1.1 (2%)	0.9 ± 0.5 (1%)	3.4 ± 2.4 (2%)	4.0 ± 2.3 (2%)	0.3 ± 0.3 (0)
Coarse roots	13.9 ± 0.8 (20%)	20.6 ± 1.9 (17%)	27.4 ± 4.2 (15%)	30.6 ± 5.7 (12%)	46.7 ± 3.7 (13%)
Fine roots	1.1 ± 0.3 (2%)	1.5 ± 0.4 (1%)	2.5 ± 0.6 (1%)	2.3 ± 0.9 (1%)	3.3 ± 0.6 (1%)
Sum	70.1 ± 2.3	120.0 ± 23.9	180.1 ± 30.3	252.8 ± 57.5	360.6 ± 45.7

Note: Values within bracket stand for tree components' biomass percentage of whole tree biomass.

Table S3.4. Proportion of tree components' types in terms of biomass and components'-specific carbon concentrations (weighted mean ± SD) of harvested trees (n=30).

Components type	C concentration (%)	Proportion (%)
Stems	42.9 ± 1.4	50.7
Major Branches	45.0 ± 1.1	18.7
Fine branches	45.7 ± 1.3	7.8
Seeds	46.7 ± 3.0	0.8
Leaves	48.2 ± 1.5	6.4
Coarse roots	43.0 ± 1.0	14.8
Fine roots	44.0 ± 3.0	0.8
Mean	43.9 ± 1.9	

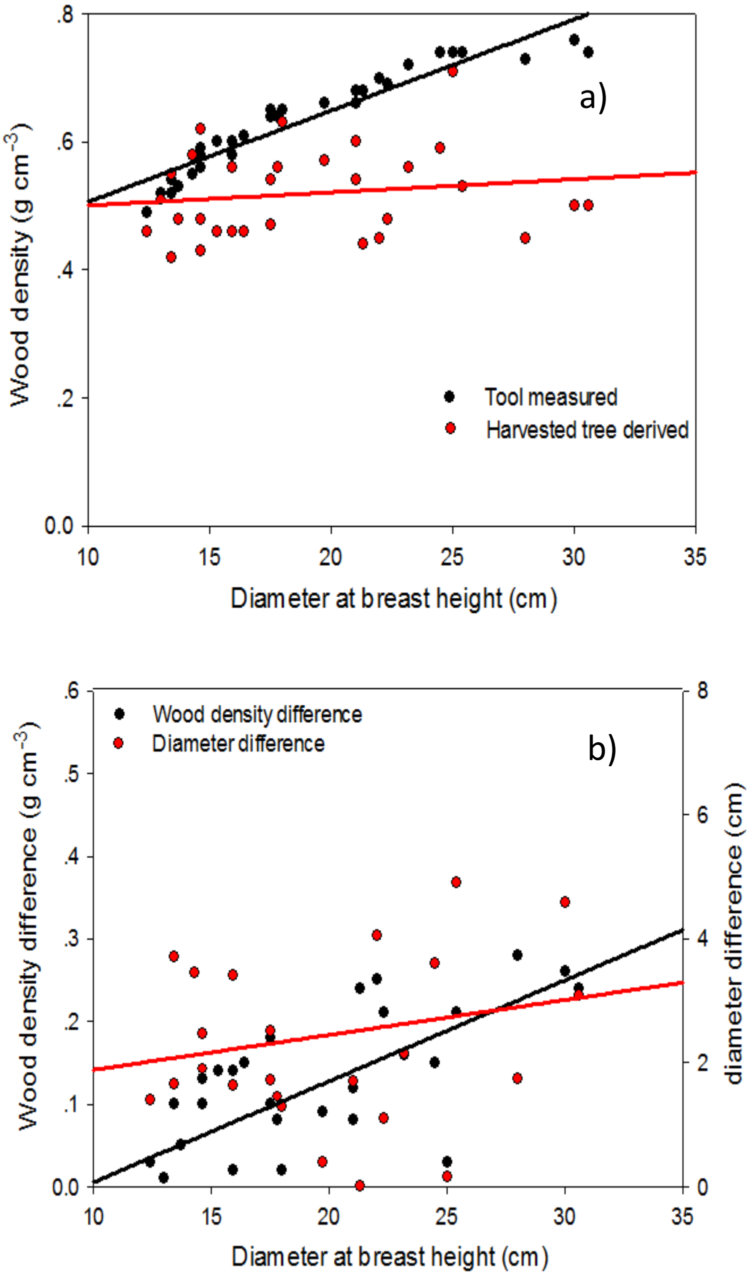

Figure S3.1. Wood density analysis: a) comparisons of two estimation approaches as a function of diameter at breast height. The data obtained with the usage of a stem borer showed a significant linear relationship (R^2= 0.89, p < 0.0001) between DBH and mean wood density of each sampled tree, while the harvested tree derived approach did not show a significant linear relationship (p = 0.4149); b) for each sampled rubber tree, the plotted wood density difference between tool measured approach and harvested tree derived approach, together with their difference in sampled diameter length.

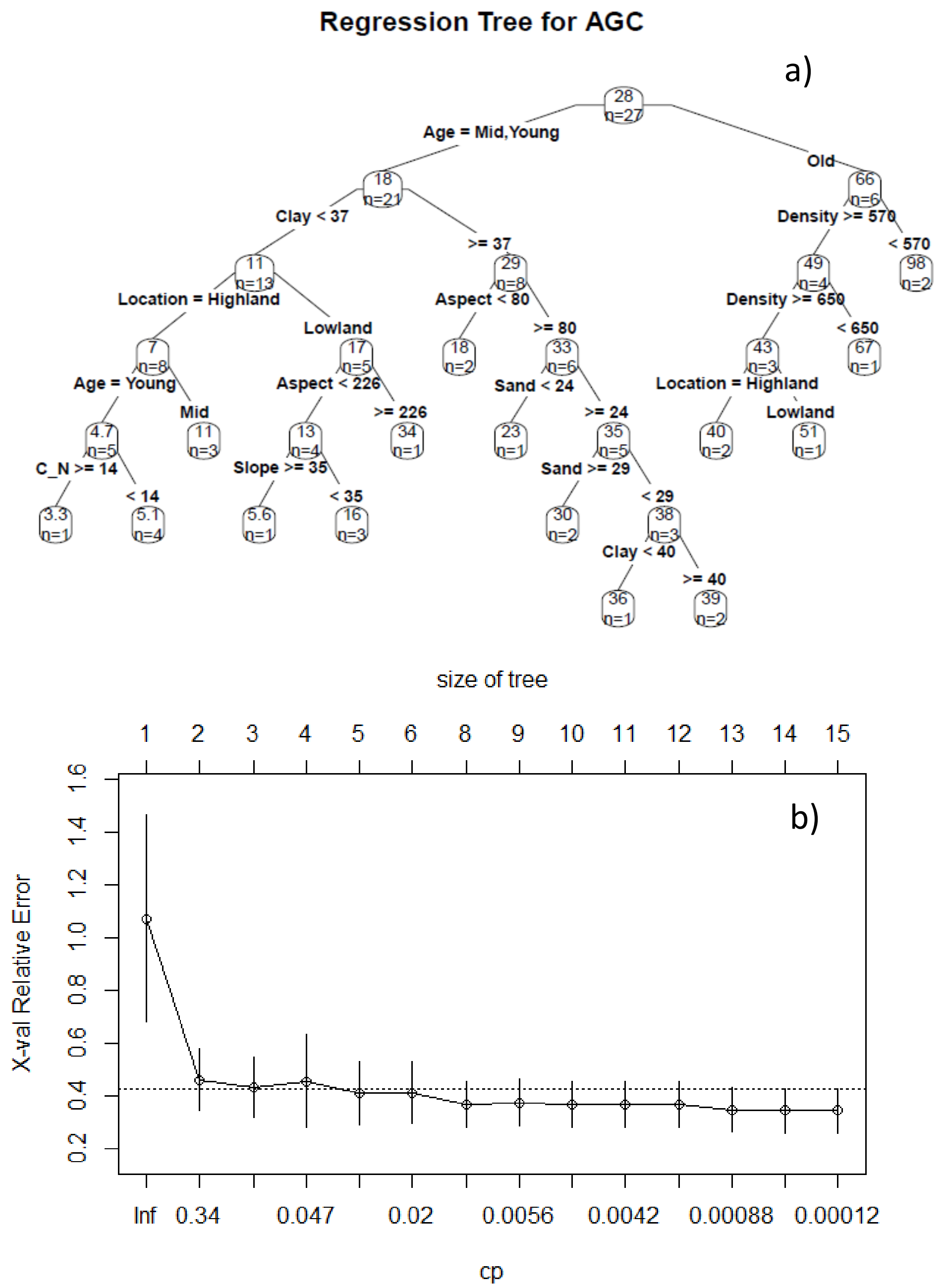

Figure S3.2. The relationships between AGC (aboveground carbon) and environmental factors according to the classification and regression tree (CART) analysis in a mountainous landscape of China. The un-pruned tree (a) and tree size and relative error (b) in the process of the CART are shown. Age (young, mid-aged, old aged plantation; year); Clay (soil clay concentration percentage, %); Sand (soil sand concentration percentage, %); Density (stem density, trees ha^{-1}); location (highland, lowland rubber plantation; meter.a.s.l); C/N (dimensionless unit); Slope (°); Aspect (°).

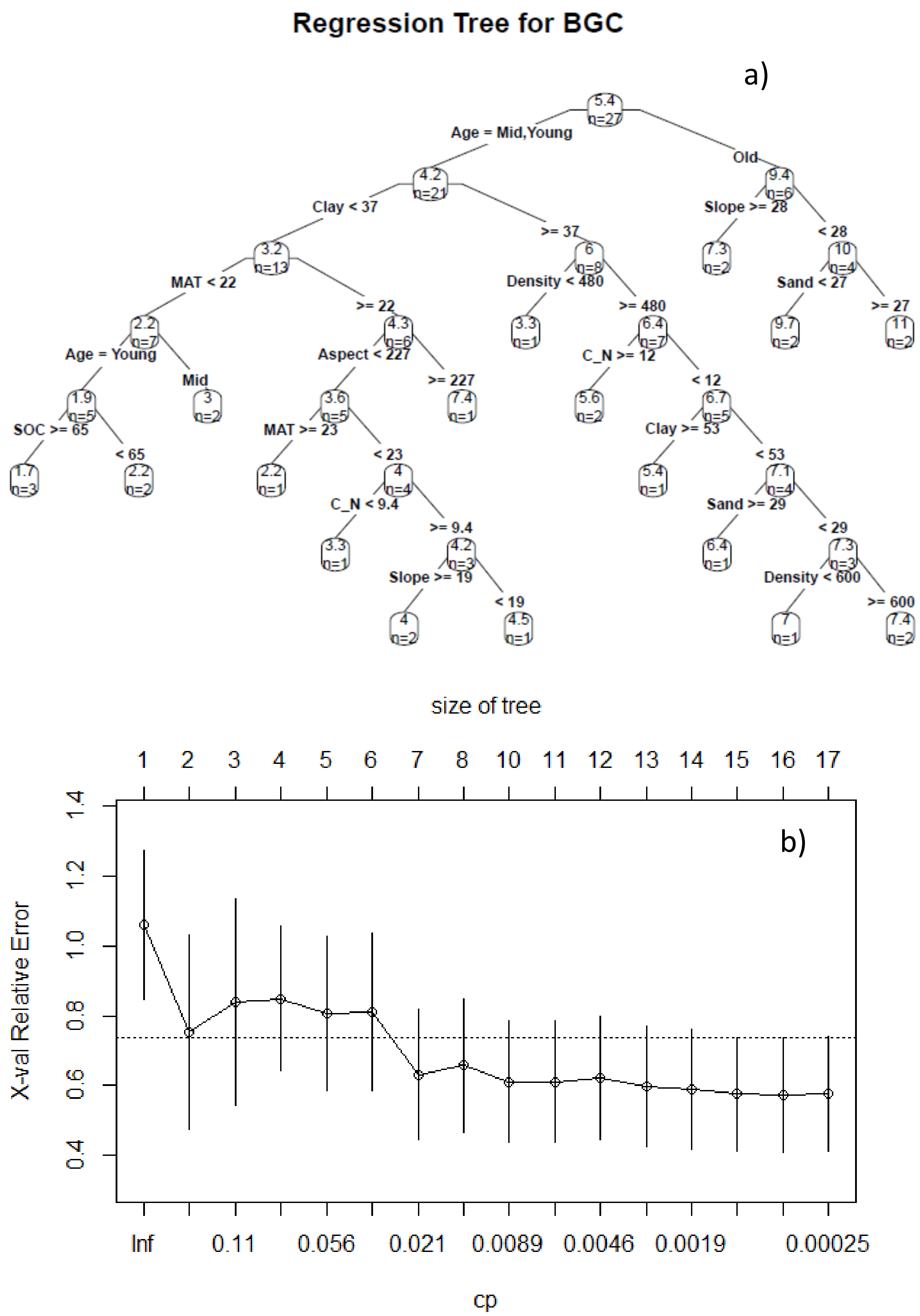

Figure S3.3. The relationships between BGC (aboveground carbon) and the environmental factors according to the classification and regression tree (CART) analysis in mountainous landscape of China. The un-pruned tree (a) and tree size and relative error (b) in the process of the CART are shown. Age (young, mid-aged, old aged plantation; year); Clay (soil clay concentration percentage, %); Sand (soil sand concentration percentage, %); Density (stem density, trees ha^{-1}); C/N (dimensionless unit); Slope (°); Aspect (°); MAT (mean annual temperature, °C); SOC (soil organic carbon, Mg ha^{-1}).

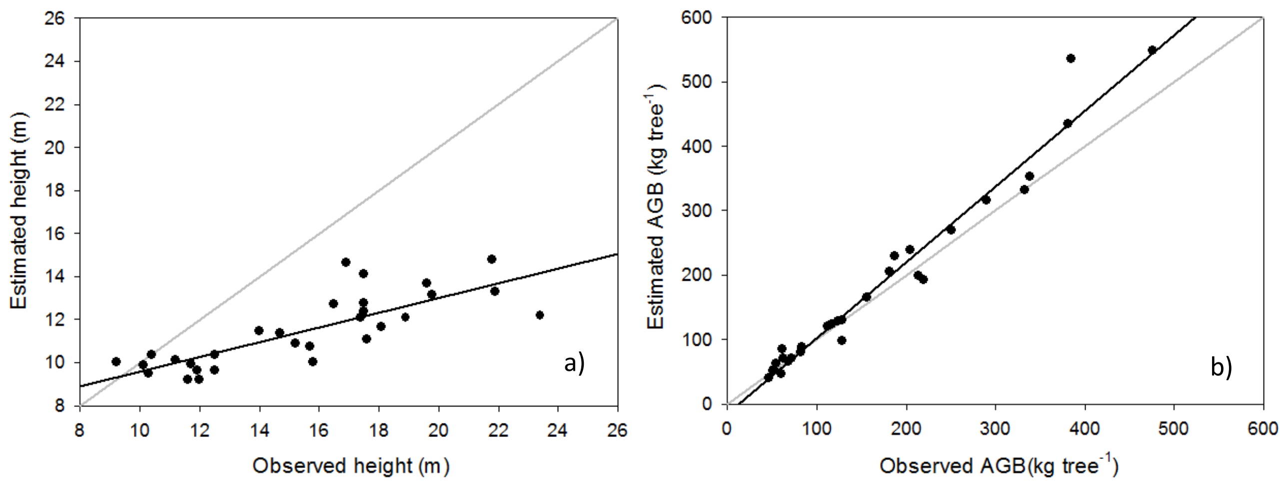

Figure S3.4. Application of pan-tropical forest allometric equations for rubber tree biomass prediction. Measured versus a) predicted tree height by using equation 6a from Chave et al. (2015) and b) above ground biomass by using equation 7 from Chave et al. (2015) are shown.

Chapter

4

Climbing mountain fast but smart? Modelling rubber tree growth and latex yield under climate change

Chapter 4 Climbing mountain fast but smart: modeling rubber tree growth and latex yield under climate change[3]

Xueqing Yang[a,b,c], Sergey Blagodatsky[a], Carsten Marohn[a], Hongxi Liu[a], Reza Goblon[a], Feng Liu[d], Xu Jianchu[c], Georg Cadisch[a]

[a] *Institute for Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim, Stuttgart, Germany*

[b] *Key Laboratory of Economic Plants and Biotechnology, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, China*

[c] *World Agroforestry Centre (ICRAF), China & East Asia Office c.o. Kunming Institute of Botany, Kunming, China*

d *Bureau of Naban River Nature Reserve, Yuanlin alley 19#, Jinghong, 666100, China*

[3] **This chapter has been submitted as:**
Yang, X.Q., Blagodatsky, S., Marohn, C., Liu, H.X., Goblon, R., Xu, J.C., Cadisch, G., 2018. Climbing mountain fast but smart: modeling rubber tree growth and latex yield under climate change. To: Forest Ecology and Management. Under review.

Abstract

Pará rubber (*Hevea brasiliensis* Müll. Arg) plantations have expanded into regions with cooler temperatures and distinct dry seasons. The impact of these new marginal environments and future climate change on rubber tree development and latex yield is largely unknown. This makes it difficult to reliably predicting farmers' revenues and determine carbon sequestration at landscape level. To improve our understanding of how rubber trees respond to altitudes > 900 m above sea level (a.s.l.) and associated high planting densities, we applied the process-based Land Use Change Impact Assessment tool (LUCIA) calibrated with detailed ground survey data to model tree biomass development and latex yield in rubber plantations at the tree, plot and landscape level. Plantations were analysed at < 900m a.s.l. (lowland rubber) and ≧ 900m a.s.l. (highland rubber) in order to characterize the effect of elevation on rubber trees in Xishuangbanna, southwest China. Three planting densities were tested: low- (< 495 trees ha^{-1}), medium- (495 - 600 trees ha^{-1}) and high-planting density rubber (> 600 trees ha^{-1}). Four greenhouse gas emission scenarios, with Representative Concentration Pathways (RCP) ranging from the lowest RCP 2.6 to the highest emission scenario RCP 8.5, were used to test rubber tree response to climate change. During a 40-year rotation, lowland rubber plantations grew quicker and had larger latex yield than highland rubber. The average biomass of lowland rubber was 9% and 18% higher than highland rubber for aboveground and belowground biomass, respectively. High planting density rubber plantations showed 5% higher above ground biomass than those at low- and medium-planting density. In Xishuangbanna, Southwest China, optimum biomass and latex yield involves planting rubber at elevations < 800 m a.s.l., at densities < 600 trees ha^{-1}. The mean total biomass and cumulative latex yield per tree over 40 years increased by 28% and 48%, respectively, when climate change scenarios were modelled from baseline to RCP 8.5. Denser plantations produced lower biomass and latex yield per tree. The same trend of biomass and latex yield increase with climate change was observed at plot level. Denser plantations had larger biomass, but the cumulative latex production decreased dramatically. The results produced during landscape modelling could help maximize carbon stock and latex production of regional rubber plantations. Other rubber cultivation regions could also benefit from this modelling approach, updating with region-specific environmental information. Given the projections on climate change,

such an approach may be crucial for sustainable rubber cultivation and management.

Keywords
landscape modeling, land use change, carbon sequestration, planting density, marginal area

4.1 Introduction

Rubber plantations in Southeast Asia were originally established in Malaysia, Indonesia and Southern Thailand. With increasing market demand, rubber plantations rapidly expanded into Montane Mainland Southeast Asia (MMSEA) over the last several decades (Fox et al., 2014). This area of > 2.1 million ha is defined as land > 300m above sea level (a.s.l.), covering Southwest China, half the land area of Cambodia, highlands and coastal areas of Vietnam, northern Thailand, Laos and Myanmar (Priyadarshan et al., 2005; Fox et al., 2014). A rapid rubber expansion from 87,111 ha in 1988, to 189,764 ha in 2002, and 424,552 ha in 2010 (Xu et al., 2014; Chen et al., 2016) occurred in Xishuangbanna prefecture, located in southern Yunnan, China. Owing to the expected high financial returns compared to other agricultural crops, farmers currently cultivate rubber at elevations up to 1400 m a.s.l. (Chen et al., 2016). A 6-month delay in attaining a tappable girth of rubber tree was reported for every 100 m rise in elevation above 200 m a.s.l.; this correlates with a 0.6 °C temperature decline for every 100 m increase in elevation (Dijkman 1951; Moraes 1977). Elevation gradients exhibit gradual micro-climate change, with progressive changes in temperature and precipitation. Soil properties like nitrogen availability for plants (Garten Jr. and Van Miegroet 1994) and turnover time of labile soil carbon (Garten Jr. and Hanson, 2006) also vary along a climate gradient associated with changes in elevation. Differences in phenology (leaf shedding, leaf flushing, leaf maturity, flowering and fruit growth) exist between sub-optimal growing conditions and regions more suitable for rubber planting. Water use and latex production are closely linked to active leaf area, and seasonal leaf growth dynamics are the main determinant of plant resource assimilation and economic return for rubber plantations (Cotter et al., 2017). Variation in solar radiation intensity near the equator and in the subtropics explains these differences (Priyadarshan and Sasikumar, 2001; Yeang, et al., 2007). Studying the response of rubber tree growth, latex production and phenology along an elevation gradient is essential in the context of extending rubber cultivation to new upland areas, as well as for adaption strategies under a changing climate. Rubber trees have slower growth rates when cultivated in sub-optimum environmental conditions where rubber is vulnerable to typhoon, drought, chilling, frost injury and landslide risks (Yoshino, 1990; Chapman, 1991; Clermont-Dauphin et al., 2013; Ahrends et al., 2015; Liu et al., 2015). Yang et al. (2016) reported a 52% lower time-averaged carbon stock at higher elevation areas. Nguyen (2013) explored the dependence of latex productivity of rubber plantations on elevation, and found a negative relationship between elevation and latex productivity in Vietnam. Rubber tree growth and latex productivity are also highly influenced by local farmers' practices, which might modify the response resulting from environmental conditions (Blagodatsky et al., 2016). For example, optimizing planting density can compensate for yield loss caused by strong typhoons and cold damages in South China (Qi et al., 2016). The negative impact from tapping panel dryness can also be minimized by adopting a low-tapping frequency system in rubber plantations (Senevirathna et al., 2007). Judicious application of herbicides and maintaining the understory helps minimize soil loss and maintains biodiversity (Liu et al., 2016). Therefore, optimum rubber tree growth and latex production should be considered a result of the combined impact of environmental factors and management activities. Many studies have explored effects of individual factors (climate, soil, or management) on rubber tree growth and latex yields (Jiang, 1988; Wauters et al., 2008; Yi et al., 2014a; Yu et al., 2014; Golbon et al., 2015). However, the integrative effect from multiple factors towards rubber tree long-term growth and production remains unclear. The lack of scientific knowledge of this holistic view hinders the ability to provide guidance for the cultivation and sustaining of rubber plantations.

Temperature and precipitation are considered as major limiting factors in plant growth, set by minimum requirements to fully develop key tissues (Lenz et al., 2014). Suitable temperature for rubber latex synthesis is 18 - 28°C, while favorable temperatures for latex flow are 18 - 24°C (Shuogang and Yagang, 1990; Kositsup et al., 2009). The optimum temperature for photosynthesis in rubber trees is 27 - 33°C (Xu, 1988). Temperatures below 5°C will damage the trees, while temperatures exceeding 40°C will restrict plant growth and young leaf generation (Zongdao and Xueqin, 1983; Zhou, 2008). Although future global warming could actually provide more suitable areas for rubber cultivation in current marginal regions (Zomer et al., 2014), the growth response and latex yield under such climate change scenarios has not been fully examined. However, more extreme temperatures and precipitation on a regional scale could lead to a serious decrease in natural rubber productivity, with the inherent regional socio-economic consequences (Satheesh and Jacob, 2011; Jayasooryan et al., 2015). Nguyen and Dang (2016) tested the temperature dependence of natural rubber productivity in southeastern Vietnam (elevation ranges from 15-200 m a.s.l.) and found an inverse correlation between rubber production and both mean monthly temperature (*Tmean*) and monthly minimum temperature (*Tmin*). They hypothesized that *Tmin* influences latex flow, while *Tmean* affects latex regeneration thus explaining how these 2 climatic parameters have a net effect on rubber tree productivity. As with any hypothesis this needs further investigation to clarify the mechanism. In rubber-cultivating regions of Xishuangbanna, there are 2 dominant rubber management strategies, smallholder-owned and state-owned rubber plantations. Plantations located in regions lower than 900m a.s.l. are usually high profit and state-owned; those at higher elevation are mostly low-profit belong to smallholders (Gibreel et al., 2014). Tree densities on state-owned farm sites average around 495 trees ha^{-1}, considerably lower than the 580 - 850 trees ha^{-1} on smallholdings (Yi et al., 2014a). Based on these results from previous studies, we posed two hypotheses: 1) compared with rubber plantations cultivated in areas with temperatures optimal for growth, plantations in marginal colder areas could benefit from global warming, resulting in higher biomass accumulation and latex productivity; and 2) intensively managed plantations with denser tree stands might benefit less from climate change, owing to pre-existing competition between trees.

In climate change research, consideration of alternative scenarios helps to evaluate complex interactions of climate, ecosystems and human activities. The Intergovernmental Panel on Climate Change (IPCC) has focused on developing a new generation of scenarios, namely Representative Concentration Pathways (RCP), to provide projections of greenhouse gas emissions, atmospheric concentrations of these gases and land use/cover for climate modelling (Moss et al., 2010; IPCC, 2014). There is a need for models to similarly project the potential impact of climate change on long-term patterns of forest growth and development in a format accessible to forest managers (Wang et al., 2013). Ideally, such models should: 1) be capable of representing the effects of climate change on forest productivity and drought-related mortality, 2) have the ability to simulate a variety of forest management options to allow for an evaluation of different adaptive management strategies, 3) provide broad outputs relevant to multi-objective forest management, and 4) be relatively straight forward to calibrate and validate. There are currently a number of models available for simulating climate impact on forest productivity. These models include process-based stand models, terrestrial biogeochemical models, hybrid models, carbon accounting models, gap models and dynamic global vegetation models. The major difference is in their simulated spatial scale (forest stand, patches, regions or global), level of empiricism (process-based, or hybrid), and whether species distribution changes are included (Medlyn et al., 2011). Models that have been applied to rubber trees include: process-based models, namely Physiological Processes Predicting Growth (3-PG; Landsberg and Waring, 1997), Soil Vegetation Atmosphere Transfer (SVAT; Kumagai et al., 2013), Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS; Van Noordwijk and Lusiana, 1999) and Land Use Change Inpact Assessment (LUCIA; Marohn and Cadisch, 2011); and hybrid models CO_2FIX (Schelhaas et al., 2004), and the Bio-economic Agroforestry Model (BEAM; Grist et al., 1998; Table 4.1). The application of empirical models is largely restricted to areas where the trees were measured, as these models do not allow changes in the main factors that affect tree growth such as, climate, water availability, and silvicultural management (Korzukhin et al., 1996; Monserud, 2003). An alternative approach is to exploit the dynamic capabilities offered by process-based models that predict forest growth, at the same time identifying and quantifying the main factors that can potentially increase or reduce productivity. Such models predict yields under both stable and variable climatic conditions, including those associated with climate change (Hlásny et al., 2011; Sánchez-Salguero et al., 2017). In addition, if fully parameterised, they can allow for high yield genotype selection and advances in site preparation through silvicultural practices (Sands et al., 2000; Sands and Landsberg, 2002). The application of a process model to a large area requires spatially explicit information, which could represent driving or constraining variables at landscape level (Ditzer et al., 2000). The choice of the LUCIA model in this study was determined by the following factors: 1) the model has been calibrated and tested for different kinds of forests and environments, including rubber plantations in Thailand and Vietnam (Marohn et al., 2013; Lippe et al., 2014); 2) it includes an improved latex yield prediction module and unique plantation options allowing for the dynamic simulation

Table 4.1 Models used for rubber plantation system simulation.

Model type	Model name	Spatial scale	Time steps	Modules	Applications	Source
Process-based models	3-PG	Stand, landscape	Month, year	Production of biomass; biomass partitioning, stem mortality, soil water balance, stand properties	Used for rubber plantations tapping scheme, plant disease and pest control	Zhu and Jiang, 2010
	SVAT	Stand	Hour or half hour	Energy, water and radiation conservation model; ecophysiological model; turbulent diffusion model	Simulates CO_2 and H_2O fluxes from the canopies of rubber plantations, suggesting a potential optimal spacing.	Kumagai et al., 2013
	WaNuLCAS	stand	Daily	Climate; tree; crop; planting schedule; soil, water and nutrient; tree products (rubber latex).	To simulate rubber-intercropping system biomass development; land and water management for rubber productivity	Boithias et al., 2012; Cahyo et al., 2016;
	LUCIA	stand, Landscape	Daily	Soil, water balance, plant/crop growth, management, nutrient translocation	Potential for estimate rubber biomass partitioning and latex production with consideration of soil-water balance.	Marohn and Cadisch, 2011
Hybrid models	CO_2FIX	regions	Year	Biomass; soil; products; bioenergy; financial; carbon accounting	1) To estimate the efficiency of increasing rotation length as article 3.4 of the Kyoto Protocol.	Nizami et al., 2014
					2) To test three rotations' management impacts on carbon sink.	Egbe et al., 2012
	BEAM rubber agroforesty model	regions	Year	Coupled with biological model and economic model	To assess the impacts from biomclimatic, topographic and sivicultural factors on rubber output (latex, timber), integrated with economic model to test the price and climate uncertainties.	Purnamasari et al., 2002

of management strategies; and 3) the model is spatially explicit and can generate outputs both at stand and landscape level, and therefore, can assist in regional decision making. Most of these outputs can be tested against observed data to evaluate model accuracy.

Using LUCIA combined with an intensive ground survey, we attempted to answer the following questions: 1) How do different altitudes and planting densities affect rubber tree growth and production under present and future climatic conditions? 2) How can management strategies with planting densities in marginal expansion areas (at high elevation) increase carbon sequestration? LUCIA was calibrated using plot-level survey data covering a wide range of different stand characteristics (age, productivity and planting density) for rubber trees in the Southwest China. Integration of climate data from General Circulation Models (GCM) in LUCIA modelling along with daily temporal resolution can allow one to project the impact of various RCPs scenarios on both biomass production and latex yield. Modelling results help to understand the biophysical processes of forest development in a managed landscape. They can be further integrated with socio-economic information to identify trade-offs between the optimization of tree growth and maximization of economic benefits. Thus, the model results can be used for guiding sustainable management in rubber-cultivating regions.

4.2 Material and methods

4.2.1 Study area

The study site was located in the Naban River Watershed National Nature Reserve (Naban reserve), Xishuangbanna, China. The total protected area is 26,660 ha (22°04′ - 22°17′ N, 100°32′ - 100°44′ E) within an elevation range of 539 - 2304 m a.s.l. The area has distinct dry (November - April) and rainy seasons (May - October). The annual rainfall varies from 1200 - 1700 mm, and the mean annual temperature range is 18 - 22°C (YEPB, 2006). The Jinghong weather station record was collected through the Meteorological Data Sharing Service System (http://data.cma.cn/en), including the average temperature, precipitation and relative humidity for 1954 - 2013. The temperature anomaly in the recordings of this region and other climate data are reported in Figure 4.1.

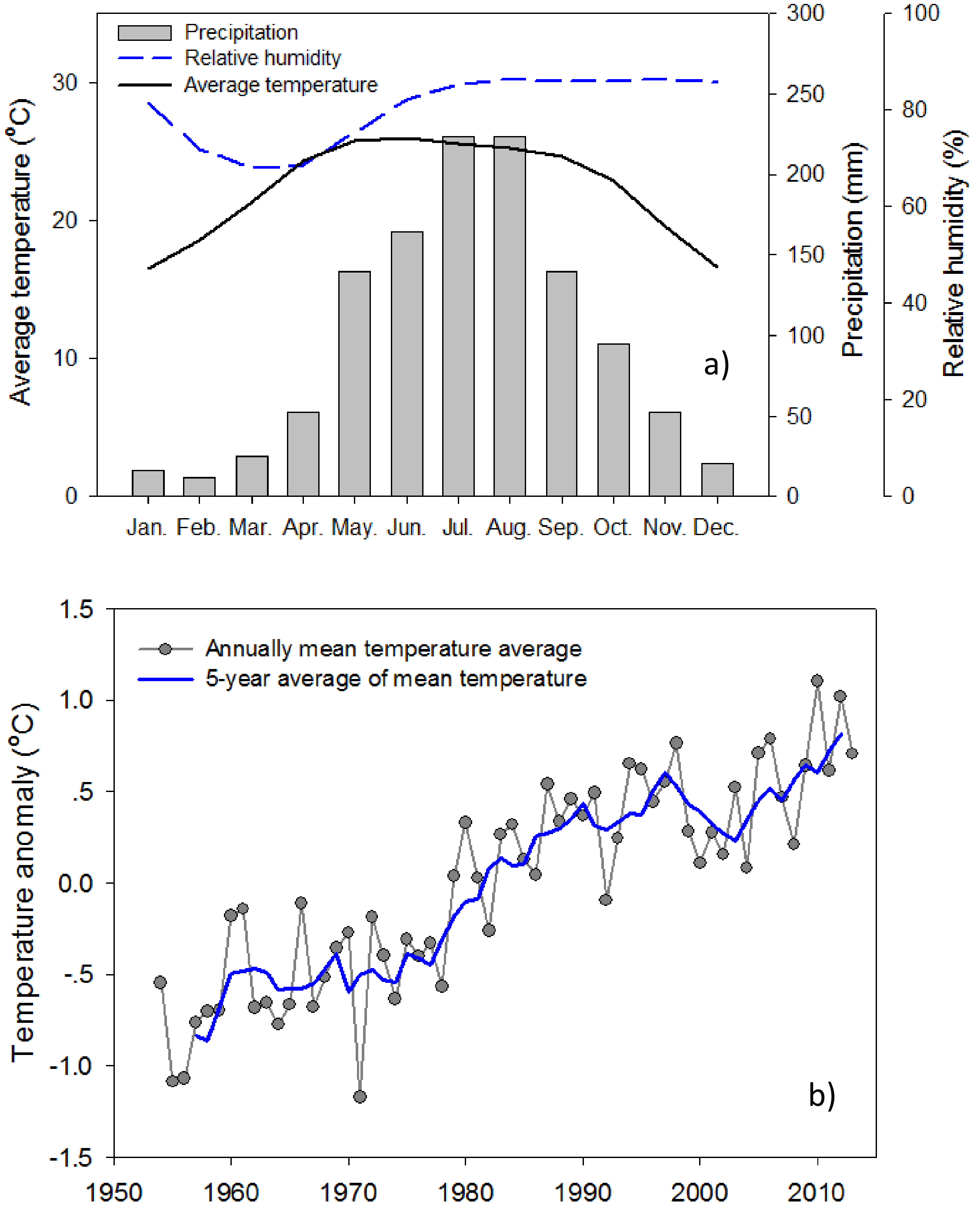

Figure 4.1. a) average monthly temperature, relative humidity and precipitation accessed from the Jinghong airport long-term record (1954-2013); b) annually mean temperature anomaly (difference between the long-term average temperature and the temperature that was recorded) from1954-2013.

The major soil type is Ferralsol (Apel, 1996), whereas minor soil types are Regosols (FAO/UNESCO, 1998). Rubber trees were first introduced in this region in the 1980s and are currently mostly distributed in the buffer and experimental zones of the reserve (Yang et al., 2016) below 1200 m a.s.l. In this region, rubber trees behave as deciduous trees with defoliation occurring between December and February. In early February leaf expansion starts, followed by flowering within 2 weeks. The rubber fruits ripen in August and mainly fall down during September (Jia et al., 2006). More than 95% of the rubber plantations in the Naban reserve belong to smallholders (YEPB, 2006). From 1989 to 2012, the lowland rubber plantation area in the Naban reserve increased from 274 ha to 1149 ha, while the highland rubber plantation area increased from 64 ha to 1709 ha (Yang et al., 2016). Rubber tree planting densities in the Naban reserve range from 360 to 900 trees ha^{-1} (Yang et al., 2016). We designed a general evaluation framework for the present study shown in Figure 4.2. The impact of climate as well as local management practices (cultivation elevation and planting density) were assessed, using available field data and process-based modelling.

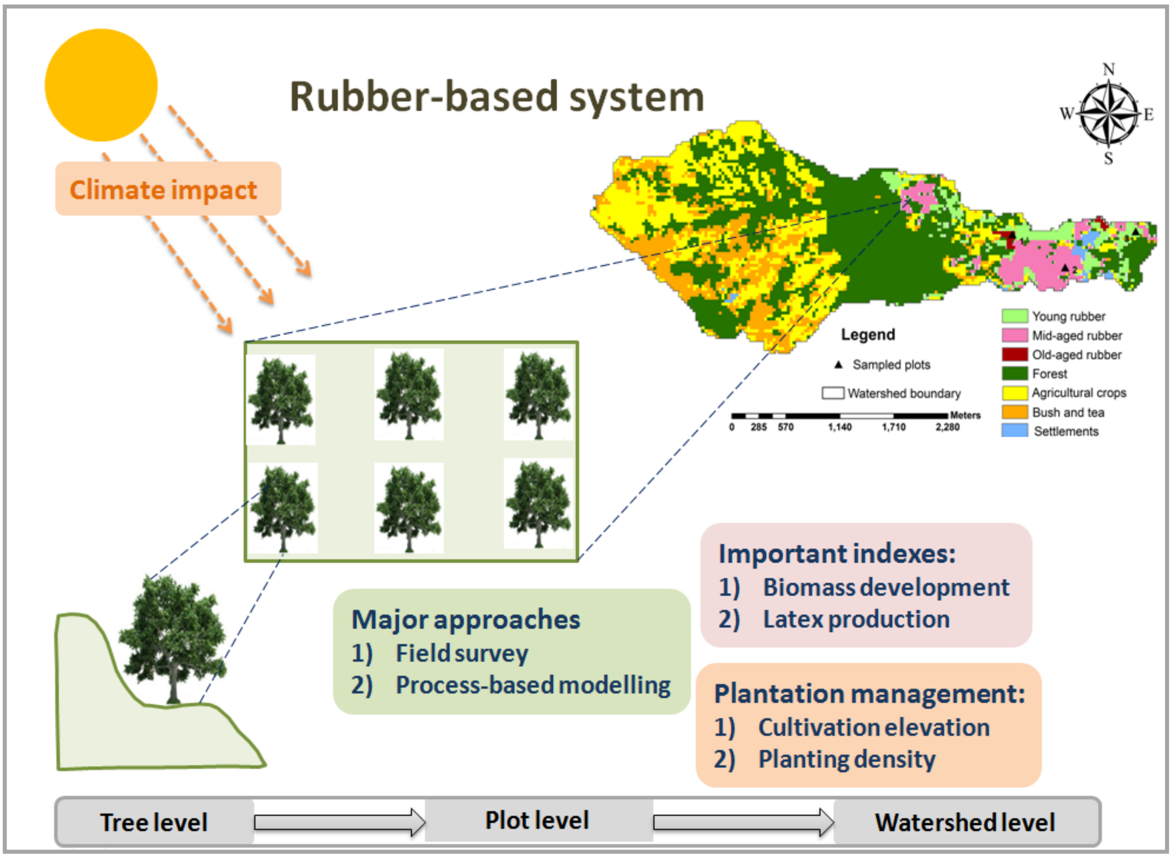

Figure 4.2. General framework of the study, presenting evaluation approaches for rubber trees/plantation growth and latex production. Climate impacts as well as local management effects were assessed.

4.2.2 Data acquisition and preparation

4.2.2.1 Rubber tree growth and latex yield data collection

Parameters for modelling were mainly based on data obtained from rubber plantations in the Naban reserve. In the lowland area of the Naban reserve, we set up 3 permanent plots (20 x 25 m) in existing young (4-year), mid-aged (12-year) and old-aged rubber (35-year) plantations. Data on litterfall and leaf area index (LAI) were collected each month from January 2014 to February 2015. Square litterfall traps (nylon gauze with 1 m^2 surface area and 2.0 mm mesh,) were suspended at a height of 1.0 m from the ground using 4 PVC pipes. Nine litterfall traps were set up for each rubber plantation age (Supplementary material Figure S4.1). Litter was sorted into 4 categories: leaves, twigs, reproductive parts (flowers, fruits, and seeds) and miscellaneous. Twigs were oven-dried at 105℃ and other components at 85℃ to constant weight; they were then weighed and the mean monthly litter mass (Mg ha^{-1}) was calculated. Specific leaf area, (SLA; m^2 kg^{-1}), was measured according to Bouriaud et al. (2003). One-sided area of 30 leaves from different stand age rubber trees were scanned and analysed using Image J software (https://imagej.nih.gov/ij/download.html). An indirect LAI measurement of light absorption using SunScan (Delta-T Devices Ltd, Cambridge, UK) was applied to estimate dynamic changes of leaf area index (LAI) during a whole year. The annual cumulative leaf dry weight from the litter traps was determined. The maximum leaf area index (LAImax) for sampled rubber plantations was calculated by multiplying leaves dry weight with SLA. A total of 30 rubber trees with root profile up to 2 m in depth were harvested, and 882 rubber trees were measured non-destructively in 27 plots in order to establish allometric equations and calibrate detailed rubber tree parameters (for details see Yang et al., 2016 and Yang et al., 2017). The sampled rubber plots covered rotation lengths of 4 - 35 years, elevation gradients of 621 - 1,127 m a.s.l., and locally used clone types GT1, RRIM 600, and Yunyan77-4, in mountainous Southwestern China. Two years of continuous latex yield data (2009 - 2010) from this same area was used for model calibration and validation (Golbon et al., 2015). For further model validation data was used from a household survey of smallholder rubber farmers in Xishuangbanna conducted in 2013 (Min et al., 2017). A total of 612 smallholders from 42 villages in 8 townships of the 3 counties in Xishuangbanna (Menghai, Jinghong and Mengla) were interviewed. The smallholder farm characteristics including stand age, planting density, location, elevation and corresponding latex yield were compared with model outputs. Further tree parameters were derived from the literature as detailed in Table 4.2.

4.2.2.2 Climate data

Input climate data needed for LUCIA included daily average air temperature, precipitation, solar radiation and reference evapotranspiration. Historic daily climate records for 1954 - 2013 from Jinghong airport weather station, the nearest weather station 20km from the study site, were used for a baseline run (http://data.cma.cn/en). Projected climate data used for model prediction were derived from the ensemble of 19 Earth System Models (ESM) provided by the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) for the fifth assessment period of the Intergovernmental Panel on Climate Change (IPCC). Four emission scenarios, the Representative Concentration Pathways (RCPs; IPCC 2014) included, RCP 2.6 (Van Vuuren et al., 2007), RCP 4.5 (Smith and Wigley, 2006; Clarke et al., 2007; Wise et al., 2009), RCP 6.0 (Fujino et al., 2006; Hijioka et al., 2008), and RCP 8.5 (Riahi et al., 2007), in order of increasing emissions. These scenarios represented radiative forcing of 2.6, 4.5, 6 and 8.5 Wm^{-2}, respectively by the end of the 21st century. Zomer et al. (2014) analysed the CMIP5 model predictions for the year 2050 (average value of future climate 2040 - 2060) and downscaled them, using the Delta method (Ramirez and Jarvis, 2010), to 30 arc-sec resolution (equivalent to ~1km^2 at the equator). The outputs from CMIP5 were used as the reference for future climate change scenarios. Therefore we followed the projected mean annual temperature (MAT) and mean annual precipitation (MAP) change in Xishuangbanna region for 2050, namely RCP 2.6 (MAT increase 1.6℃, MAP increase 2.1%), RCP 4.5 (MAT increase 2℃, MAP increase 2.4%) and RCP 8.5 (MAT increase 2.4℃, MAP increase 2.5%) and uniformly increased daily climatic input in LUCIA model. The daily correction of climate data was done using plot-specific MAT and MAP data derived from the maps of Zomer et al., 2014. We also considered the seasonal changes, in precipitation and temperature in our future climate change scenarios. We selected RCP 4.5 as the representative intermediate emission scenario for the present study.

Table 4.2. Interval values and source of species-related parameters used for model parameterization of *Hevea brasiliensis* Müll. Arg growth and development.

Description	Parameters (unit)	Unit	Value	Bibliography
Management	Fertilizer amount	kg/ha/yr	400	Dong et al., 2015
	N	kg/ha	30	
	P	kg/ha	30	
	K	kg/ha	30	
	Manure	kg/ha		
	Tapping frequency	dimensionless	0.5	Golbon et al., 2015
	Start tapping season	dimensionless	20, Apr	
	End tapping season	dimensionless	30, Nov	
	Starting tapping DBH	cm	16	
	Planting density	trees/ha	360-900	Golbon et al., 2015; Yang et al., 2016
Physiological stress	N supply	dec %	0	
	N supply	dec %	0	
	N supply	dec %	0	
	Water supply	dec %	1	
Rubber physiology	LAI initial	m^2/ m^2	1	This study
	LAI critical	m^2/ m^2	6.5	
	Specific leaf area	m^2/kg	13	This study
	Root max	cm	400	
	Fine root density	Mg/m^3	0.003	
	Root shape	m/m	0.5	
	Kc	dimensionless	0.9	FAO,http://www.fao.org/docrep/x0490e/x0490e0c.htm
	Drought adaption	dimensionless	2	
	T base	°C	16	Shuogang and Yagang, 1990; Yu et al., 2014
	Toptlow	°C	25	
	Topthigh	°C	30	
	Tmax	°C	40	
	Flower degree day	degree day	320	Calculated based on Phenology record from Jia (2006)
	Harvest degree day	degree day	2400	
	Albedo plant	dimensionless	0.15	
	Stem maintenance respiration	kg(CH_2O)ha/d	0.001	
	leaves maintenance respiration	kg(CH_2O)ha/d	0.015	
	leaf turnover time	day	120	
	root turnover time	day	70	
	coarse root proportion	dimensionless	0.2	This study
	Parameter controlling allocation to roots	dimensionless	0.25-0.5	
	Parameter controlling allocation to leaves	dimensionless	0. 5	
	Parameter controlling allocation to harvestable (fruits and tubers)	dimensionless	0.01-0.05	
	crown radius max	m	4	This study
	crown radius initial	m	0.5	
	LAI start branching	dimensionless	4	
	crown radius/crown height ratio	m/m	0.5	
	trunk shape	dimensionless	1	
	wood density	g/cm^3	0.64	Yang et al., 2017
	a' value stem allometry	dimensionless	0.05	
	b' value stem allometry	dimensionless	2.7	

Soil properties	topsoil thickness			Yang et al., 2016; Liu et al., 2016
	subsoil thickness	cm	15	
	Bulk density topsoil	cm	80	
	Bulk density subsoil	mg/m^3	1.13	
	Soil organic carbon topsoil	mg/m^3	1.41	
	Soil organic carbon subsoil	%	3.18	
	top/subsoil at field capacity	ml/cm^3	0.39	
Model settings	Pixel length	m	30	This study
	Graphic latitude of catchment	radians	0.820	accessed from the SURUMER project
	Land-use/ cover map	m	30	
	Soil map	m	30	prepared from soil particle size distribution dataset (Wei et al., 2012; http://globalechange.bnu.edu.cn/)
	Area map	m	30	Prepared from land-use/cover map
	Digital Elevation Model v2 data	m	30	ASTER Global Digital Elevation Map (https://asterweb.jpl.nasa.gov/gdem.asp)
	Local Drainage Direction map	m	30	Prepared from DEM.

4.2.3 Modelling approach

4.2.3.1 Plant growth modelling

LUCIA model is an ecological process-based model, simulating plant-soil-hydrology relationships at the landscape level. The projected regional daily climatic data and process-based approaches were integrated in order to predict rubber tree physiological responses to future climate change scenarios (Figure 4.3). The crop model in LUCIA is based on the World Food Studies – Crop Growth Simulation Model (WOFOST-CGMS; Supit 2003) with the transpiration concept adapted from Allen et al. (1998). A detailed description of LUCIA could be found in Marohn and Cadisch, (2011). This model simulates tree growth based on the following key assumptions: (1) biomass is first formed from photosynthesis and differentiated into 4 types of plant tissues, leaves, stems, roots and fruits; (2) depending on plant development stage, different plant organs grow at different rates based on resources allocation; and (3) tree growth is controlled by biotic and abiotic factors such as temperature, precipitation, solar radiation, evapotranspiration, soil water and nutrient content. The implementation of climate-related functions in LUCIA made it a useful tool in the study of the response of tree species to climate change.

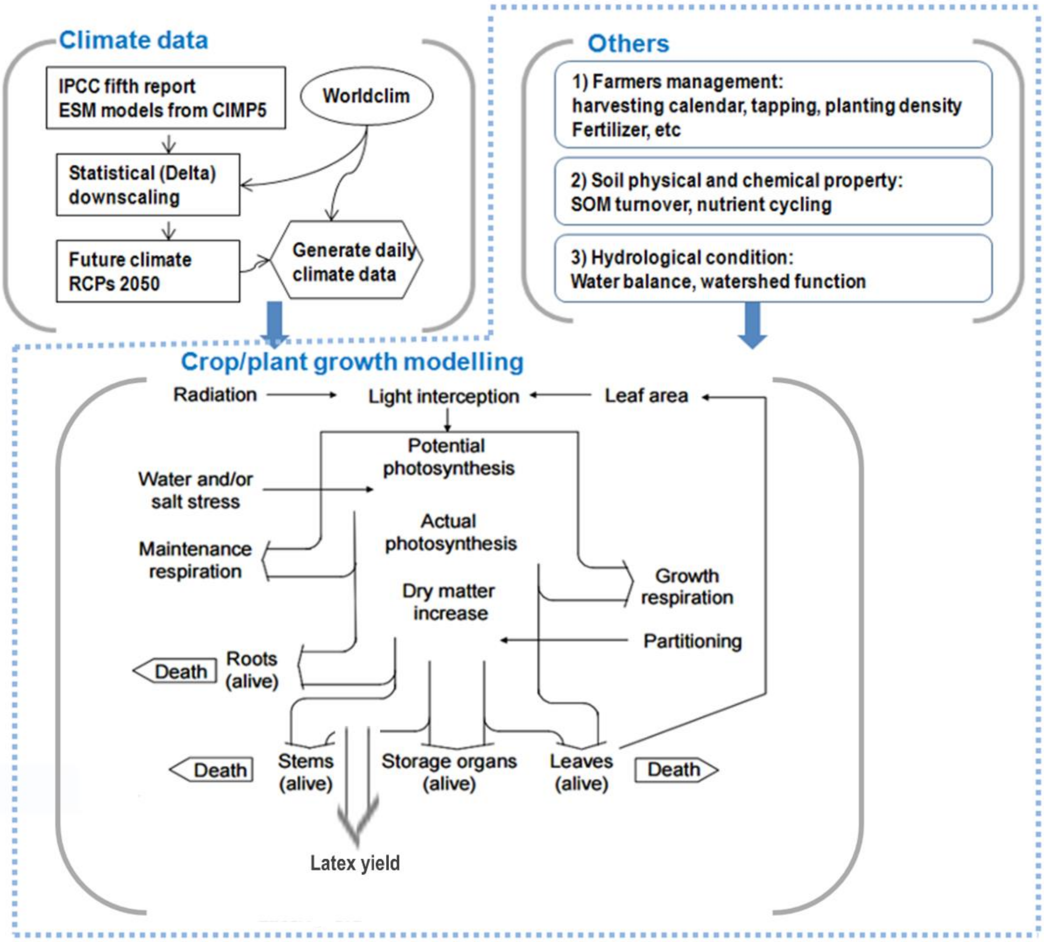

Figure 4.3. Crop/plant growth processes and driving factors incorporated in LUCIA model. Dashed line stands for processes in LUCIA model, revised from WOFOST model (after Kropff and Van Laar, 1993; Supit 2003).

In the LUCIA plant growth module, daily assimilation depends on day length, photosynthetically active radiation (PAR), LAI, and crop- and development-specific maximum assimilation rates, as well as the respired fraction of assimilated carbon. The current model version allows single tree growth simulation in ‘plantation mode.’ The tree and tree stand development thus depend not only on tree specific parameters such as initial and maximum crown radius, critical LAI value, timing of branching (lateral expansion of the crown), but also on tree planting density (intra and inter row distances). Therefore, this feature provides the possibility of modelling the effects of competition between trees and planting density on tree growth (van Noordwik et al., 2011).

Plant LAI (m^2 m^{-2}) is estimated by net leaf growth biomass (ΔWn_{leaf}, Mg ha^{-1}) and specific leaf area (SLA, m^2 kg^{-1}), an index used to measure leaf thickness. The respective equation reads:

$$LAI_t = LAI_{t-1} + \Delta Wn_{leaf} * SLA * 0.0001 \quad (4.1)$$

ΔWn_{leaf} represents leaves produced per unit time (t, day) after subtraction of leaf fall.

Daily gross CO_2-assimilation rate of a plant is calculated from the absorbed radiation by leaf layer L (I_{aL}), and the photosynthesis-light response curve of individual leaves. This response is dependent on temperature and leaf age (Boogaard et al., 2014). The I_{aL} is estimated as:

$$I_{aL} = k(1-\rho)I_0 e^{-kLAI_L} \quad (4.2)$$

where k is an extinction coefficient, ρ a reflection coefficient, I_0 (J m^{-2} s^{-1}) the radiation level at the top of the canopy and LAI_L the cumulative leaf area index at depth L.

The intercepted radiation by each leaf layer is calculated on the basis of the radiation flux at the top of the canopy and the transmission by overlying layers. The gross assimilation rate in leaf layer L (A_L, kg (CO_2) m^{-2} (leaf) s^{-1}) is:

$$A_L = A_m \left(1 - e^{-\varepsilon \frac{I_{aL}}{A_m}}\right) \quad (4.3)$$

Where A_m is the maximum gross assimilation rate (kg (CO_2) m^{-2} (leaf) s^{-1}), ε is the initial light use efficiency (kg (CO_2) J^{-1} (absorbed PAR)) of individual leaves. A_m is temperature-dependent (Spitters et al., 1989).

In LUCIA, potential plant growth is a function of growth respiration ($Respiration_{Growth}$, maintenance respiration ($Respiration_{Maintenance}$), and conversion efficiency ($Efficiency_{C2Biomass}$) of carbohydrates into biomass:

$$\Delta W = Efficieny_{C2Biomass} * \left(Respiration_{Growth} - Respiration_{Maintenance} * W\right) \quad (4.4)$$

where W is cumulative biomass (Mg ha^{-1}) and ΔW biomass (Mg ha^{-1}) increase per time step. Plant respiration depends mainly on temperature. Maintenance respiration is modelled as a species-specific and plant component-specific factor. It consumed carbohydrate energy from the growth reserve pool, and used it for maintaining existing tree biomass hierarchically from shoots/roots, and then leaves.

Constraints for plant growth in LUCIA also follows a hierarchical approach. Potential growth is determined by incoming radiation, LAI and light extinction coefficient, and is constrained by water availability. Finally, water-constrained growth is multiplied with reduction factors for available N, P and K in the topsoil over plant N, P and K demand (Marohn and Cadisch, 2011). LUCIA uses a concept based on WOFOST-CGMS to simulate water limitation for plant growth. Potential transpiration is calculated from Penman-Monteith reference evaporation corrected with a specific crop factor (*ETc*), a modification of ET0, and then reduced by an exponent combining LAI and a light extinction factor of leaves:

$$Transpiration_{Pot} = ET_C * (1 - e^{-k_{global} * LAI}) \quad (4.5)$$

Actual transpiration is derived by a reduction factor based on an empiric relationship of water depletion by crops from the soil under different soil moisture regimes. Two reduction factors constrain growth during dry (*TranspRedDrought*) and water-logged conditions (*TranspRedStagnic*), respectively. Actual transpiration is derived as the minimum of both reduction factors multiplied by potential transcription:

$$Transpiration_{Actual} = min(TranspRedDrought, TranspRedStagnic) * Transpiration_{Pot} \quad (4.6)$$

In addition to reduced growth, water stress also causes leaf death.

Plant biomass (*TB*) calculations of existing forests or plantations (Mg ha^{-1}) were initialised in LUCIA using experimental data obtained by destructive sampling, or user-defined allometric equations:

$$W = a * DBH^b * PlantingDensity * ShootRatio^{-1} \quad (4.7)$$

DBH is diameter at breast height (cm). *a* and *b* are dimensionless, empirical, user-defined coefficients and exponents, respectively, which are both ideally species- and site-specific. In this study, we fitted *a* and *b* values based on destructively established allometric equations from Yang et al. (2017). As this type of estimate referred to above-ground biomass of individual trees, multiplication with planting density (ha^{-1}) and a dimensionless root/shoot ratio was needed for initialisation of existing tree stands.

The temperature sum concept (Ritchie, 1991), expressed as degree days, is used in LUCIA to account for the influence of temperature on plant phenological development. Progress in the development stage is triggered by air temperature, once actual temperature surpassed a species-specific minimum (base temperature; *Tbase*), once phenological development started, and it increases linearly with the difference between actual and base temperature. If temperature exceeds a certain upper threshold ($T_{opt}high$), growth is limited. If it exceeds a second upper threshold (*Tmax*), plant growth stopped.

4.2.3.2 Latex yield simulation

The sub-model of latex yield (kg tree^{-1} or Mg ha^{-1}) in LUCIA is based largely on that of the WaNuLCAS model (Van Noordwijk and Lusiana, 1999). In this study we took into account management activities (tapping frequency, tapping calendar), biological characteristics (optimum latex flow, tree stem diameter, the fraction of growth resources harvested on a tapping day) and climatic conditions (temperature, precipitation, soil temperature, etc.) for a comprehensive latex yield prediction. The detailed workflow is displayed in Fig. 4.4. In LUCIA, potential latex flow depends on current stem biomass. The model user could define a minimum tree diameter required for tapping and the fraction of growth resources (*StemFractionFactor*) harvested on a tapping day. The daily potential latex flow ($Latex_{pot}$, Mg day^{-1} ha^{-1}) is then calculated as:

$$Latex_{pot} = dWst * StemFractionFactor \quad (4.12),$$

dWst is the daily stem biomass increase (Mg day^{-1} ha^{-1}). The *StemFractionFactor* is a clone specific value defining the daily allocation of stem photosynthates for latex production. According to Silpi et al. (2006, 2007), the radial growth of tapped rubber trees decreased compared to untapped trees due to a competitive reserve formation process (Chantuma et al., 2009, Laconite, 2000).

In Xishuangbanna, smallholder farmers start tapping when tree DBH has reached 16 cm; tapping rubber trees every 2 days from April until late November. Usually rubber trees are tapped systematically, from top to bottom, down one side and then down the other (Yi et al., 2014a). In the present model, we assumed that each side of a tapping panel had a length of 150 cm, and each cut consumed around 0.15 cm of bark. Then the cumulative tapping panel ($TappedPanel_{cum}$, m) per rubber tree could be calculated as:

$$TappedPanel_{cum} = TappedPanel_{cum\_before} + TappedPanel_{start} * TappingDay * \\ 0.15 * TappingFrequencey \quad (4.13)$$

where $TappedPanel_{cum\_before}$ is the cumulative size of panel already tapped before the current tap, and the $TappedPanel_{start}$ is the newly tapped panel size. When the available tapping panel decreases, a common phenomenon in old-aged rubber plantations, the tapping activities decline accordingly. Tapping day (*TappingDay*) and tapping frequency (*TappingFrequency*) were parameterised with real local conditions. The tapped latex yield is then calculated from available tapping panel, tapping days, tapping frequency and daily potential latex flow (Fig. 4.4). Subsequently, cumulative latex yield ($TappedLatex_{cum}$) is calculated from daily tapped latex (*TappedLatex).* The model could also estimate latex milk cumulative yield and latex cake cumulative yield by dividing $TappedLatex_{cum}$ by 0.35 and 0.8 respectively, assuming 35% rubber content in latex milk and 20% water content in collected rubber cake.

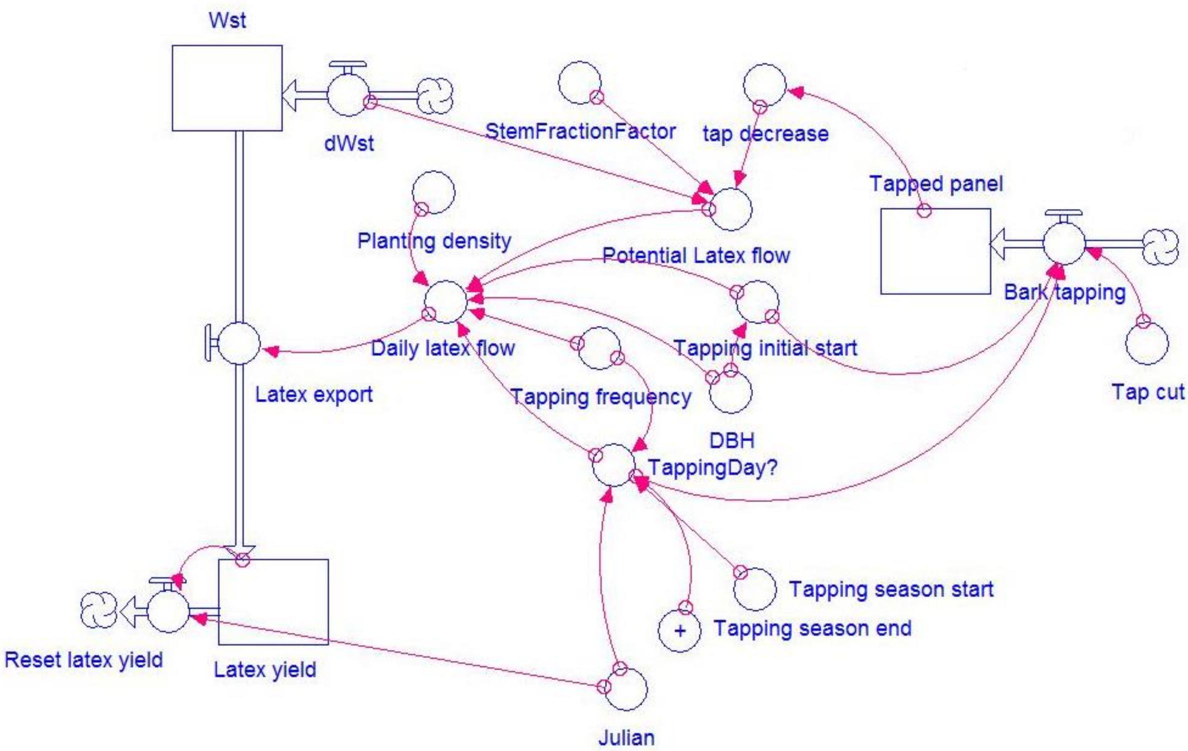

Figure 4.4. Latex simulation framework depicted in STELLA modeling shell, revised from WaNuLCAS model (Noordwijk et al., 2011). Here Wst stands for stem biomass. In present study we assumed latex generation determined by stem biomass. The tapping activity starts when the DBH of rubber trees reaches 16 cm, and stop when unavailability of tapping panel.

4.2.3.3 Model scenarios to follow the impacts of elevation, planting density and future climate

We considered elevation and planting density as 2 major parameters reflecting regional rubber plantation management, and simulated their effects on rubber growth and productivity using LUCIA. We categorized plantations into highland rubber (elevation > 900m) and lowland rubber (elevation ≤ 900m) according to the regional rubber management guidelines, to test the different response of low-profit and high-profit rubber plantations. The planting density classes were: low (low PD < 495 tree ha^{-1}), medium (medium PD ≥ 495 tree ha^{-1}, ≤ 600 tree ha^{-1}) and high (high PD > 600 tree ha^{-1}). The basis of this planting density classification was that state-owned rubber plantations in Xishuangbanna, China had on average 495 trees ha^{-1} (Yi et al., 2014a); therefore, we consider values below this level as low planting density. The upper threshold of the medium planting density was based on our ground survey from Yang et al. (2016).

We established an artificial watershed with an elevation span from 500 to 1200 m a.s.l. and variable planting densities corresponding to the surveyed planting densities at our sampled plots. Multiple simulation runs with 40-year rotation lengths and specified planting densities were completed as detailed in Figure S4.2 and Table S4.1. To avoid the effect of variable soil properties (texture or nutrition content) on plant growth, Ferralsols were used for all map pixels in this model run. We used total biomass annual production (kg $tree^{-1}$ yr^{-1}) and latex annual production (Mg ha^{-1} yr^{-1}) as representative model outputs.

The future climate change impacts on rubber plantations were evaluated by applying various RCP scenarios, they included increased MAT and MAP changes from baseline, as described in section 4.2.2.2. Development of rubber plantations, separated in 2 classes according to elevation, and 3 classes on planting density, were simulated both at tree and plot level with a 40-year rotation length. The differences in TB and cumulative latex production across various scenarios (baseline, RCP2.6, RCP4.5, RCP8.5) were evaluated using a one-way analysis of variance (ANOVA). This was followed by a least significant difference (LSD) test for multiple comparisons if the ANOVA revealed an overall significant difference. All statistical analysis, with a threshold significance score of $p < 0.05$, was performed in R (R Development Core Team, 2014).

4.2.3.4 Simulation of rubber growth at watershed level

Based on data availability, Nanhuicang watershed (697 ha) was selected as a testing site representing complex environmental interactions (Fig. 4.5 and Table 4.3). The rubber tree age map from Beckschäfer (2017) was integrated in a land-use/cover map (at 5 m resolution) provided by the project Sustainable Rubber Cultivation in Great Mekong Region (SURUMER; Yang et al., 2016), to allow the introduction of current rubber tree age distributions. Other input maps included a soil map, Digital Elevation map, and local drainage direction map, which were necessary for spatially explicit simulation (Table 4.2). In order to initialize the model with adequate settings, we classified rubber plantations into 3 age groups: young rubber (< 7 year), mid-aged rubber (7 - 20 year) and old-aged rubber (> 20 year) (Fig. 4.5a). We then used the corresponding precalibrated parameters based on survey data described above, as inputs for rubber growth simulation (Table 4.2). Young rubber growth was documented from age zero, while mid and old-aged from 7 and 20 years, respectively. The simulated results were tested against real sampled plots data with the same stand age in this region. The generated map series were exported and processed using Geographic Information Systems (GIS) software for representing tree growth and

Table 4.3 Land use and land cover types in Nanhuicang watershed and corresponding area.

Land use/land cover	Area (ha)	Percentage (%)
Forest	**323.0**	**46.3**
Upland forest	241.8	34.7
Lowland	52.9	7.6
Bamboo	28.3	4.1
Rubber plantation	**78.5**	**11.3**
Young rubber	31.8	4.6
Mid-aged rubber	43.7	6.3
Old-aged rubber	3.0	0.4
Agricultural crops	**178.9**	**25.7**
Rice	37.1	5.3
Perennial crops	16.8	2.4
Annual crops	125.0	17.9
Bush and tea	**110.3**	**15.8**
Settlements	**6.5**	**0.9**
Total	697.2	100

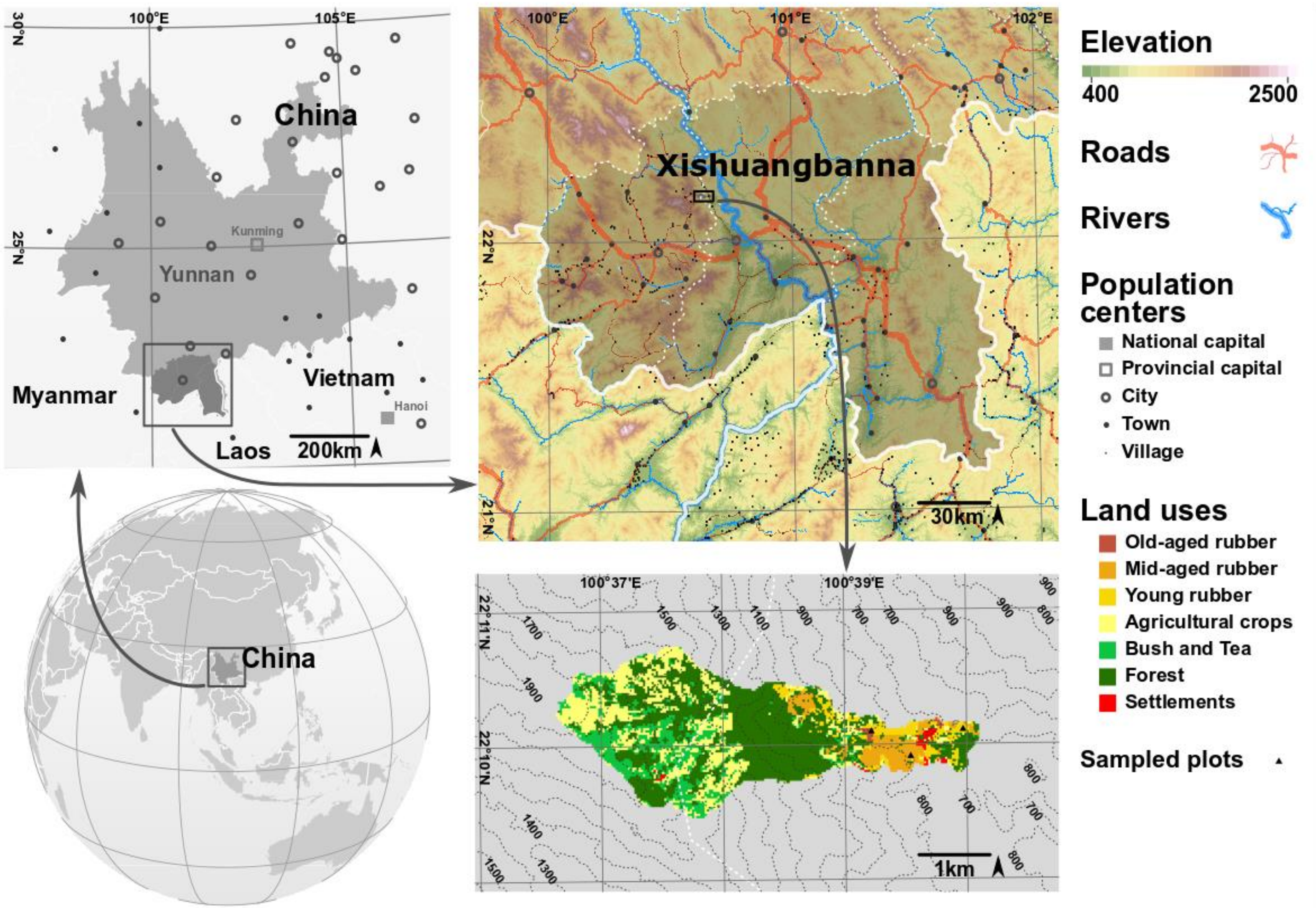

Figure 4.5 Basic information of Nanhuicang watershed in Naban reserve, Xishuangbanna, southwest China. Three surveyed plots located in young, mid-aged and old-aged rubber plantations respectively. Rubber plantations were distributed mainly in areas lower than 1200m.

productivity distribution in the landscape. All analyses and processing were carried out in Arc GIS 10.3.1 (ESRI, 2012) and PCRaster-4.1.0 (Karssenberg et al., 2010).

4.2.4 Model validation

The accuracy of model fit in respect to total biomass and latex yield was evaluated by comparison with values from the validation sub-datasets (Table 4.4). Statistical indicators used in the assessment of accuracy included: (i) root mean squared error (RMSE, Equation 4.14), (ii) relative error (RE, Equation 4.15), and (iii) model efficiency (ME; Equation 4.16). ME was the relative index of model performance estimated by directly comparing predicted and observed data. Model efficiencies ranged from 1 to -∞; 1 presented a perfect fit, while values lower than zero meant the predictions were no better than the average for that observation. Observed and predicted biomass and latex increments were plotted against the 1:1 line.

Table 4.4 Specifications for model calibration and validation for present case study

Model specification	**Model input**	**Model output**	**Source**
Tree growth			
Calibration	Wood density, "a" and "b" value for tree allometry scaling ($y = aDBH^b$)	Tree level above- and below ground biomass; DBH, tree height	Harvested rubber trees (n=30) from Yang et al., 2017
Validation	Planting density; Average and maximum biomass; Stand age Maximum LAI	Plot level above- and below ground biomass; Dynamic LAI development	Landscape level surveyed rubber plantations (n=27) from Yang et al., 2016 Present study
Latex production			
Calibration	Tapping frequency, tapping days; tree DBH starts tapping	Daily potential latex flow, daily tapped latex, cumulative latex yield, annual latex production rate	2009-2010 rubber latex tapping permanent plots, and site-specific climatic data from Golbon et al., 2016
Validation	Tapping frequency, tapping days	Cumulative latex yield, annual latex production	Based on data collected in a comprehensive survey of 612 smallholder rubber farmers in Xishuangbanna from Min et al., 2017

Note: DBH stands for diameter at breast height.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (4.14)$$

$$RE\% = \left\{\frac{(\hat{y}_i - y_i)}{y_i}\right\} \times 100 \quad (4.15)$$

where $\hat{y}_i$ and y_i are the predicted and observed values of biomass and n is the total number of data points used in fitting the model.

$$ME = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (4.16)$$

Where $\bar{y}_i$ is the mean observed value, others are same as in equation (4.14) and (4.15).

4.3 Results

4.3.1 Annual dynamics of leaf area index and latex yield used for moel calibration

Plotting measured and simulated monthly LAI values for rubber plantations of various stand ages revealed a clear seasonal pattern (Figure 4.6). When rubber trees shed all leaves in February, the SunScan monitored index of about 1 represented branches and stem index only. Leaves started regenerating 2 weeks after maximum leaf shedding, and LAI reached its highest values around July or August. During the leaf development period from March 2014 to Feb 2015, the average LAI was 2.3 ± 0.8, 4.1 ± 1.3 and 3.6 ± 1.4 for young, mid-aged and old-aged rubber plantations, respectively. Meanwhile, the average value of measured SLA was 13 $m^2 kg^{-1}$. The total annual leaf litter weights from litter traps for young, mid-aged and old-aged rubber plantations were 1.2, 3.7 and 2.9 Mg ha^{-1}, respectively; therefore, calculated maximum LAI were 1.6, 4.8 and 3.8, respectively. LUCIA-simulated LAI development dynamics showed a good fit for mid-age rubber plantation (RE = 1.9%, ME = 0.33), while for young and old-rubber plantation the model over-estimated LAI from September to December (Figure 4.6). Generally, model results exhibited a 2-month delay of leaf shedding.

The model slightly overestimated above ground biomass (AGB; RE = 15%, RMSE =

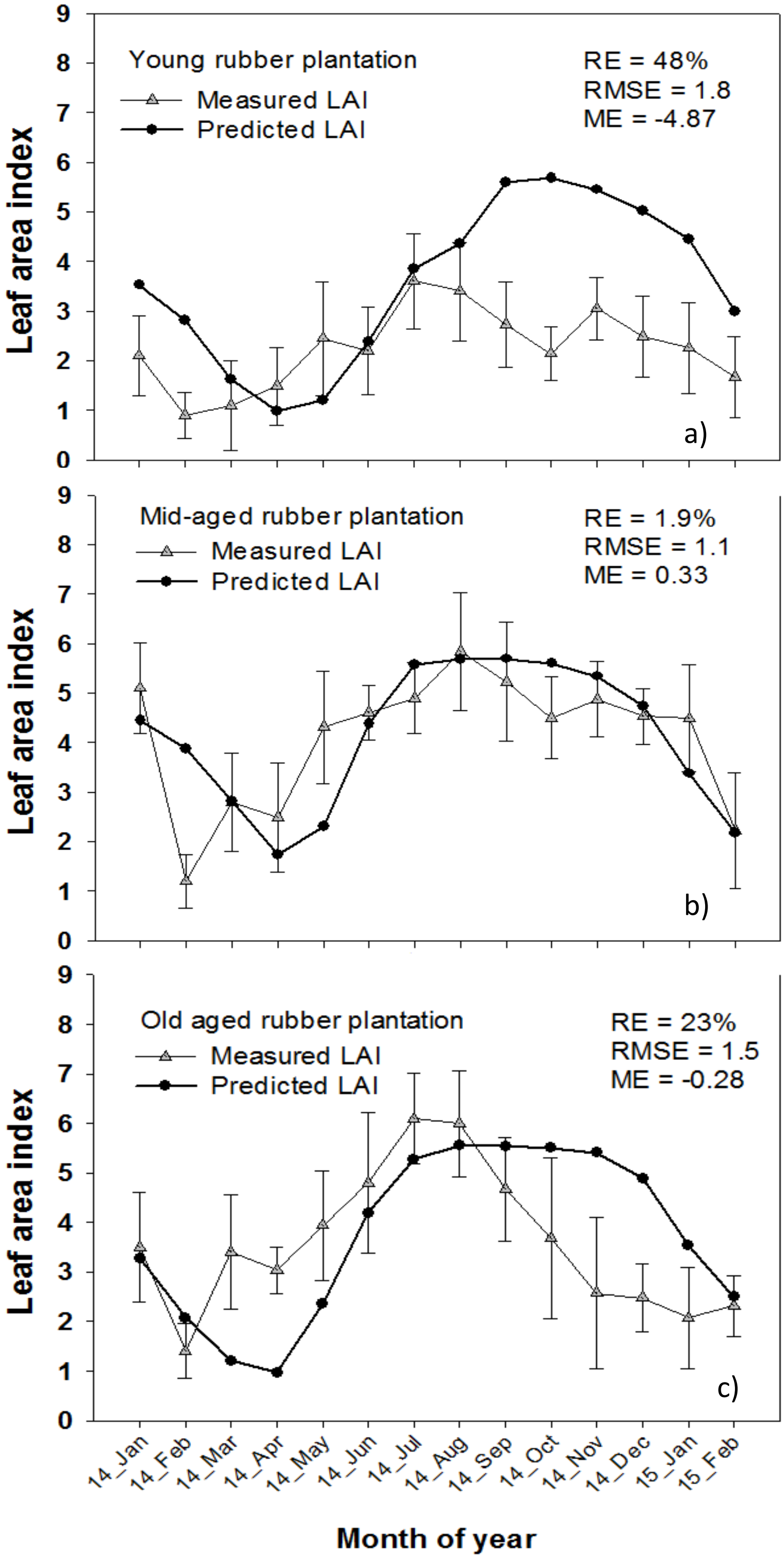

Figure 4.6. Leaf area index (LAI) measured by SUNSCAN during Jan. 2014 - Feb. 2015 and simulated by LUCIA for: a) young rubber plantation (4-year); b) mid-aged rubber plantation (12-year) and c) old-aged rubber plantation (35-year). RE is relative error, RMSE is root mean squared error, and ME is model efficiency.

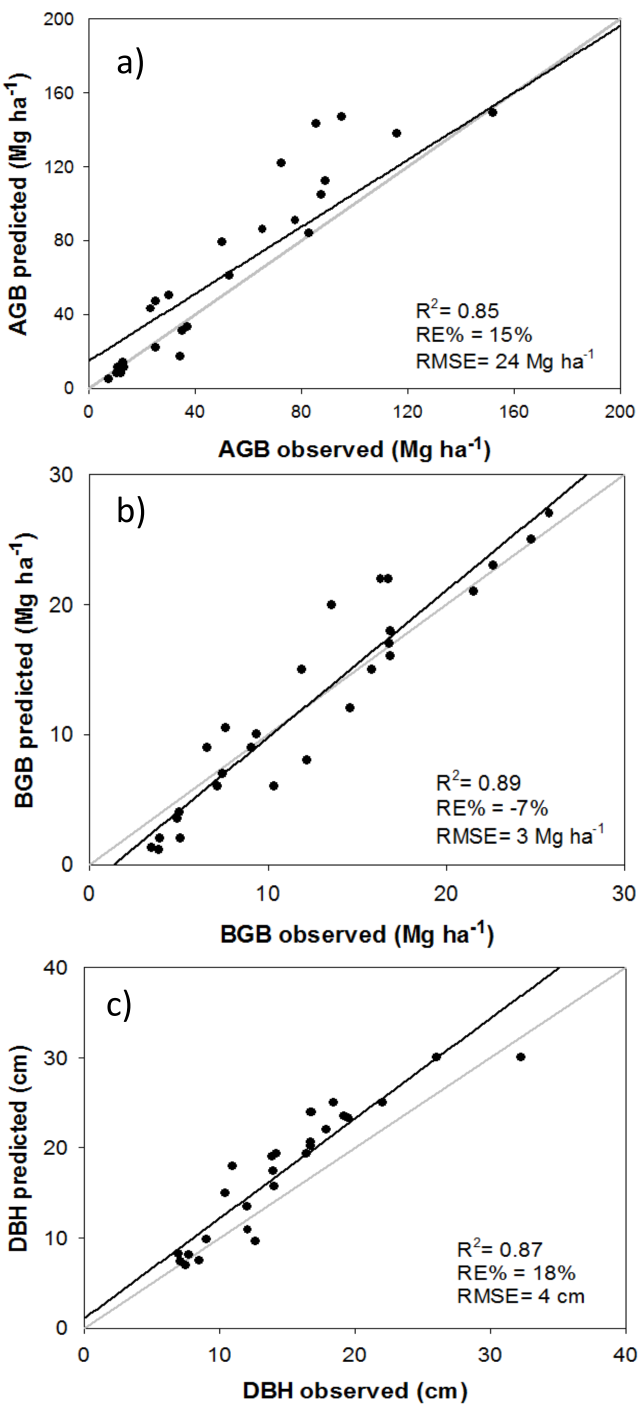

Figure 4.7. Goodness of fit for tree growth parameters: a) above ground biomass (AGB), b) below ground biomass (BGB), c) diameter at breast height (DBH). Observed data was obtained from 27 destructively sampled plots in Naban reserve, covering stand age from 4- 35 years and elevation range of 621-1127 m.

24 Mg ha^{-1}, ME = 0.82) at lower biomass yields, and underestimated below ground biomass (BGB; RE = -7%, RMSE = 3 Mg ha^{-1}, ME = 0.82) (Figure 4.7). Simulated DBH was slightly overestimated, with a bias increase for larger tree; however, general goodness of fit could be considered as acceptable. The annual measured latex yield

was slightly underestimated by the model for both 2009 and 2010 by 4% and 12%, respectively (Figure 4.8). Due to delayed leaf flushing predicted by the model (Figure 4.6), the largest underestimation of latex yield by LUCIA model was observed in spring (April until June).

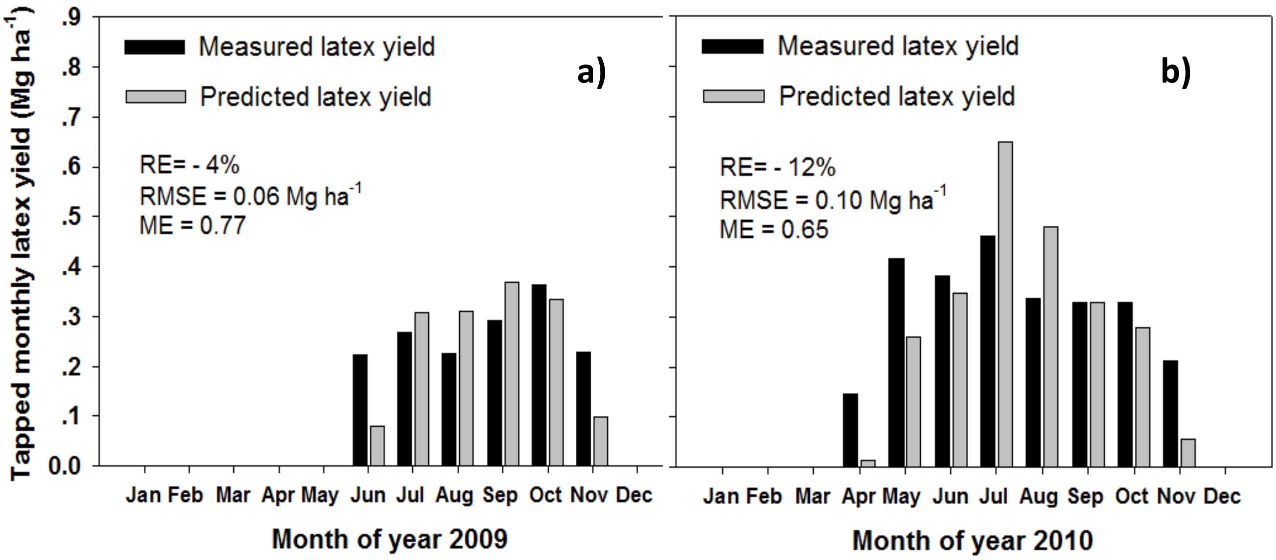

Figure 4.8. Latex yield simulated by LUCIA and measured data from one 15-year rubber plot of Goblon et al. (2015) in a) year 2009 and b) year 2010. The elevation of this plot was 680m with a planting density of 470 trees ha^{-1}.

4.3.2 Rubber growth and latex production simulated from current climate conditions: effect of elevation and planting density

Lowland rubber plantations grew faster and had a larger latex yield than highland plantations. Average measured AGB of lowland rubber was 9% higher than that of highland rubber (Figure 4.9a). The simulated cumulative latex yield during the whole rotation length was 43 Mg ha^{-1} for lowland and 35 Mg ha^{-1} for highland rubber plantations; with an averaged latex annual yield around 1 Mg ha^{-1} yr^{-1} and 0.8 Mg ha^{-1} yr^{-1}, respectively (Figure 4.9c). A major difference was in the simulated delayed tapping start of trees in highland rubber plantations at approximately 10 years of age, compared with lowland rubber starting at 8 years of age.

Planting density had a weak and variable effect on total plant biomass across rotations. Simulated AGB at the end of rotation in low-planting density plots was similar to AGB at medium planting density plots (200 and 203 Mg ha^{-1}, respectively), while high-planting density plots had a 5% higher AGB (Figure 4.9b). The simulated cumulative latex yield was 51 Mg ha^{-1}, 44 Mg ha^{-1} and 38 Mg ha^{-1} for low-, medium-and high-planting density plantations, respectively (Figure 4.9d). This was clearly influenced by a delayed tapping start in high-planting density plantations. The three planting density classes had averaged annual latex yields ranging from 0.9 - 1.2 Mg ha^{-1} yr^{-1}, with higher values at lower planting density.

The tree level simulation displayed a wide variation in TB from 2.4 to 16.3 kg $tree^{-1}$ y^{-1}. Total annual production of rubber tree biomass per plot was in the range of 1.6 - 7.7 Mg ha^{-1} y^{-1}, with on average value for all plots of 5.5 Mg ha^{-1} y^{-1} (Figure 4.10 a, c). Annual biomass production per tree was higher at low planting density (< 500 trees ha^{-1}) and elevations < 1000 m a.s.l., while annual tree biomass production evaluated at plot level also had high values at higher stand densities. The estimated annual latex productivity ($Latex_{cum}$) ranged from 1.2 - 4.6 kg $tree^{-1}$ y^{-1}. The mean annual production per tree was 1.3 kg $tree^{-1}$ y^{-1}. At plot level, the $Latex_{cum}$ annual production showed a variation of 0.6 - 1.9 Mg ha^{-1} y^{-1}, with a mean value of 0.7 Mg ha^{-1} y^{-1} (Figure 4.10 b, d). $Latex_{cum}$ annual yields per tree and at plot level were both higher in regions with low- and medium-planting densities (< 600 trees ha^{-1}) and at elevations < 700 m a.s.l. These latter model predictions were also more stable, showing more gradual changes.

We also simulated the spatial distribution of rubber biomass and latex productivity for the Nanhuicang watershed (697 ha), using a baseline scenario (Figure 4.11 a-b). The calculated total stocks of rubber biomass were 27 Mg ha^{-1}, 84 Mg ha^{-1}, and 146 Mg ha^{-1} compared to observed data of 20 Mg ha^{-1}, 72 Mg ha^{-1} and 121 Mg ha^{-1} for young (4 year), mid-aged (12 year) and old-aged (35 year) plantations, respectively. The relative model error was 25%. Based on LUCIA watershed simulations, lowland rubber plantations (< 900 m) had a mean annual total biomass increment of 6 Mg ha^{-1} yr^{-1}, and annual latex yield of 1.3 Mg ha^{-1} yr^{-1} for the baseline scenario; while highland rubber plantations had a lower mean annual total biomass increment of 2 Mg ha^{-1} yr^{-1} and annual latex yield of 0.8 Mg ha^{-1} yr^{-1}.

4.3.3 Climate change impacting on rubber tree growth and cumulative latex yield

Highland rubber tree biomass and latex production expressed per tree benefited more from climate change than lowland rubber (Table 4.5, Figure S4.3). The mean TB and

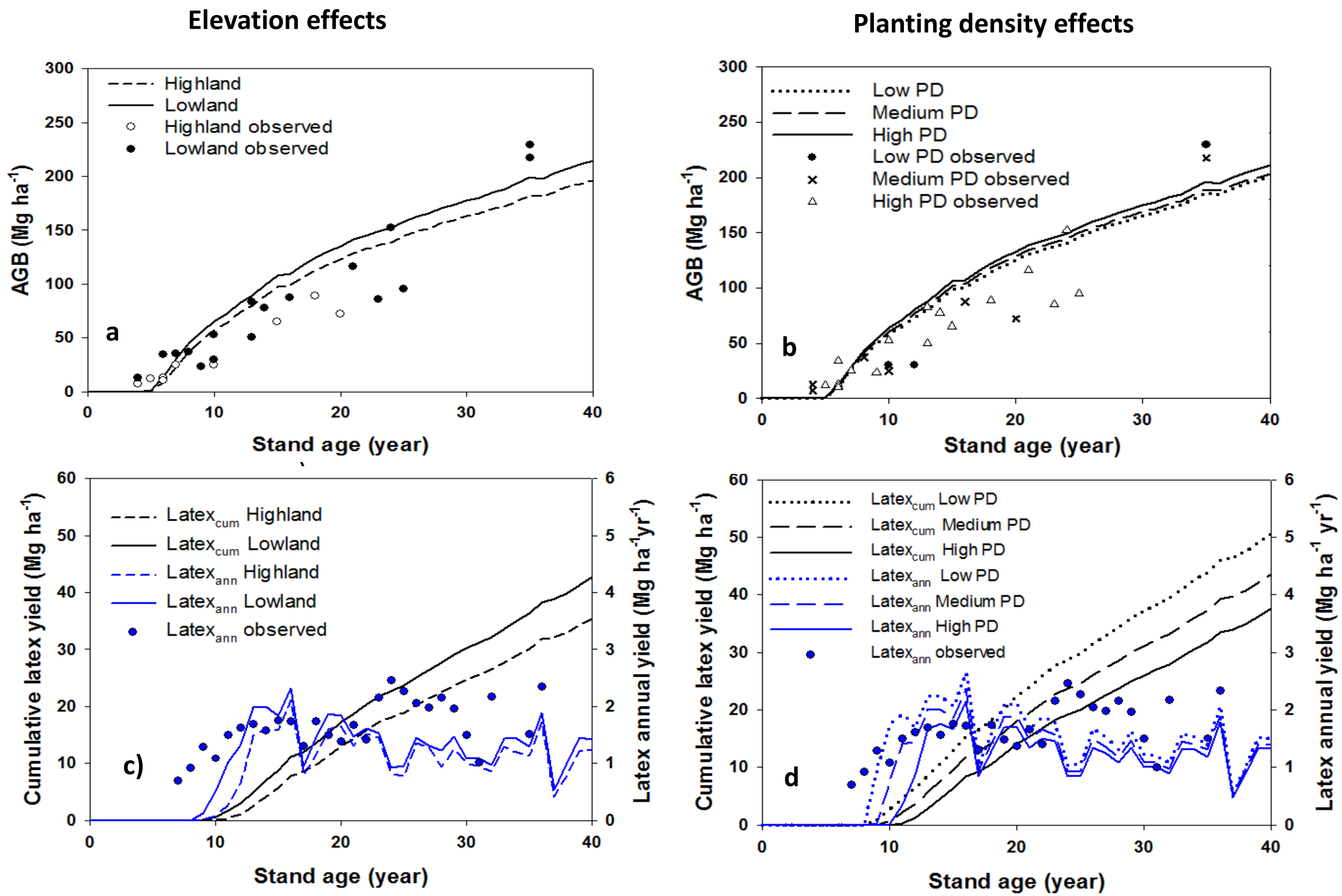

Figure 4.9. Elevation gradients and planting density effects on simulated and observed a) – b) above ground biomass and c) cumulative ($Latex_{cum}$) and annual ($Latex_{ann}$) latex production rates at current climate. Each line represents averaged simulated values for sampled rubber plantations. Sample size differed for lowland rubber (n=17), highland rubber (n=10); low (n=3), medium (n=7) and high (n= 17) planting density. Observed data points represent mean values for all classes and were taken from a smallholder interview database (Min et al., 2017).

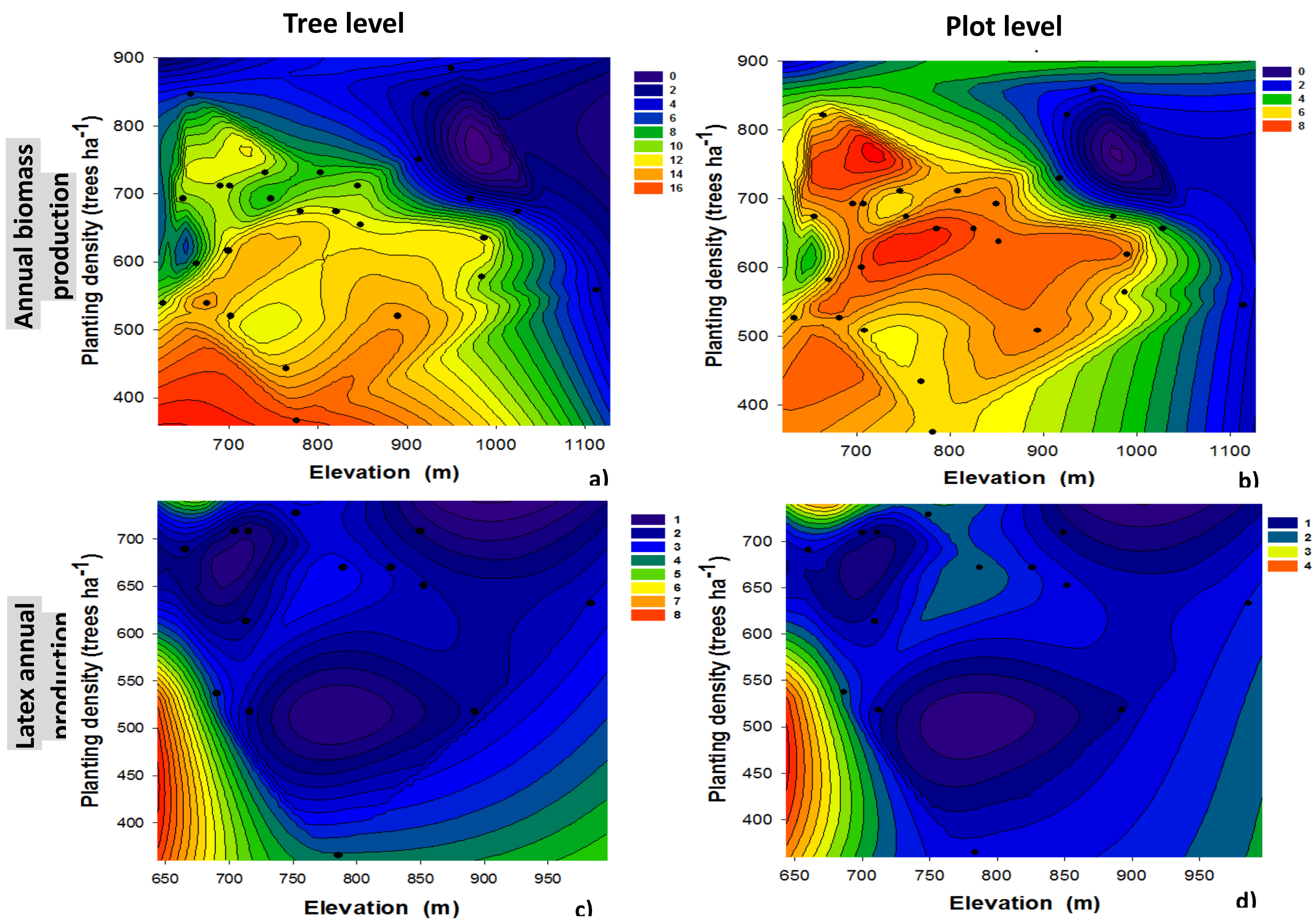

Figure 4.10. LUCIA simulated total biomass- and latex annual production changes along with planting density and elevation gradients at tree level (unit kg tree^{-1} yr^{-1}; a, c) and plot level (unit Mg ha^{-1} yr^{-1}; b, d). Figure was prepared from contour map from Sigmaplot, to show the "hotspots" of biomass- and latex annual production (from low to high value contour color changes from dark blue to red). Sampled plots for a) and b) were 27 from surveyed dataset (stand-age from 4- to 35-year), while for c) and d) were 14, here the untapped rubber plantations (plantations' stand age less than 9-year without tapping) with latex annual increment of zero were excluded.

$Latex_{cum}$ increased by 8 and 10% respectively for lowland rubber trees, when scenario RCP 8.5 was compared to baseline values; corresponding increases for highland rubber were 28% and 48%. There were no significant differences within or between elevation groups for tree TB and $Latex_{cum}$, for all climate scenarios ($P < 0.05$; Table 4.5). However, there was a strong impact of planting density on TB and $Latex_{cum}$ according to the ANOVA test. The LSD test showed a significant variance between all PD for all climate change scenarios ($P < 0.01$). Dense plantations had lower biomass and latex yield per tree over a 40-year rotation (Figure S4.3). The TB decreased approximately by 71% from low PD to high PD across climate change scenarios; the mean decrease of $Latex_{cum}$ from low PD to high PD was 129 % (Table 4.5).

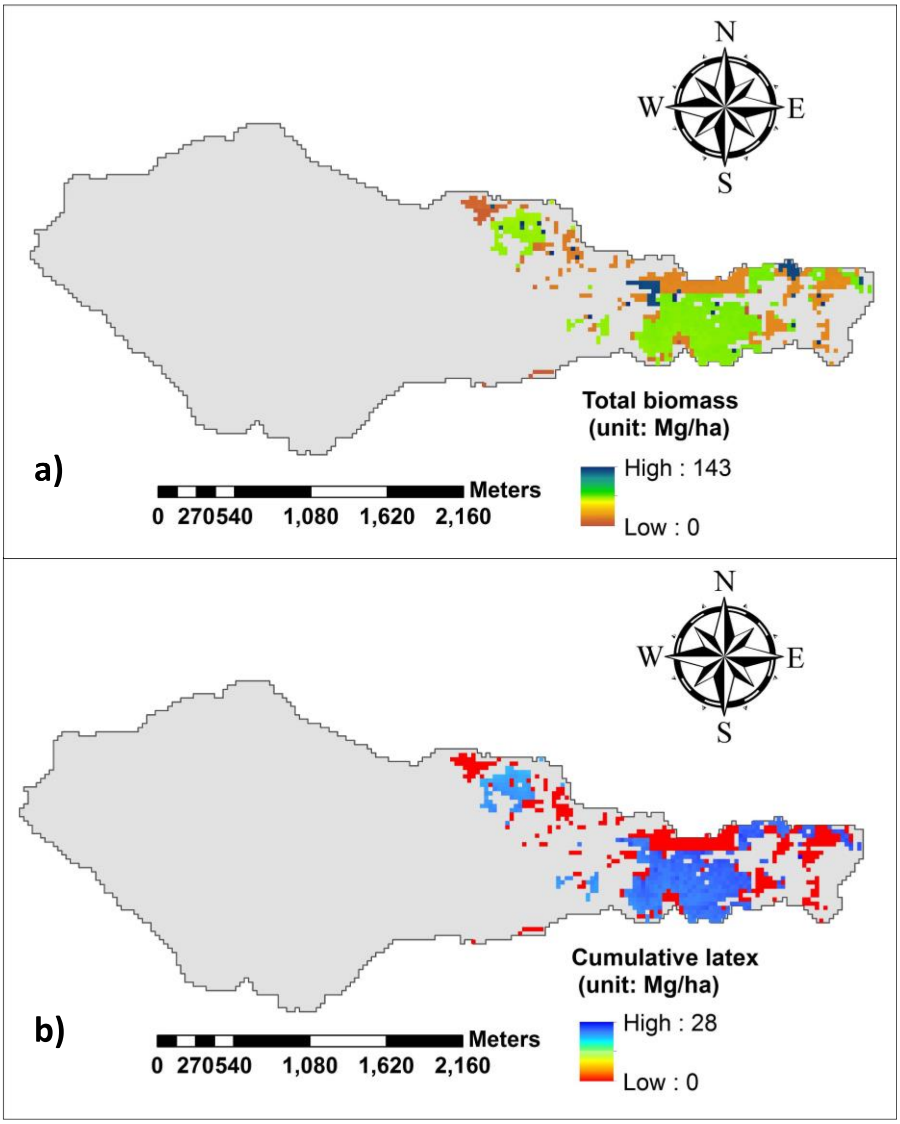

Figure 4.11. Simulated baseline (under current climatic conditions, set 40-year as one complete rotation length) of rubber outputs for Nanhuicang watershed: a) total biomass (AGB+ BGB) and b) cumulative latex production.

Table 4.5. Rubber tree growth (Total biomass) and latex production (Cumulative latex) (average ± standard error) under various management strategies (cultivation elevation and planting density level) at plot and tree level (tree age is 40-year). Significant differences based on ANOVA test across various climate change scenarios are shown. P stands for significant value between and within groups for each category, e.g. Low elevation (⩽ 900 m a.s.l.) and Highland (elevation > 900 m a.s.l.), or Low- (< 495 tree ha^{-1}), Medium- (PD ⩾ 495 tree ha^{-1} ⩽ 600 tree ha-1), High PD (> 600 tree ha^{-1}) in each climate change scenario.

Tree level					
Total biomass	Lowland	389 ± 21	423 ± 25	423 ± 25	421 ± 25
(kg tree^{-1})	Highland	327 ± 19	401 ± 22	408 ± 23	419 ± 23
	P	0.069	0.573	0.696	0.954
	Low PD	552 ± 36	624 ± 42	629 ± 42	629 ± 42
	Medium PD	415 ± 20	471 ± 14	474 ± 14	477 ± 14
	High PD	323 ± 8	366 ± 9	368 ± 9	370 ± 10
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Cumulative latex	Lowland	71 ± 7	80 ± 8	79 ± 8	78 ± 8
(kg tree^{-1})	Highland	54 ± 6	76 ± 7	77 ± 7	80 ± 7
	p	0.100	0.721	0.861	0.847
	Low PD	122 ± 12	143 ± 13	144 ± 13	142 ± 13
	Medium PD	79 ± 6	96 ± 4	96 ± 4	96 ± 5
	High PD	52 ± 2	63 ± 3	63 ± 3	63 ± 3
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Plot level					
Total biomass	Lowland	241 ± 2	262 ± 1	262 ± 1	260 ± 1
(Mg ha^{-1})	Highland	219 ± 6	269 ± 5	274 ± 5	281 ± 5
	P	**<0.001**	**0.047**	**0.002**	**<0.001**
	Low PD	226 ± 1	256 ± 1	258 ± 1	258 ± 1
	Medium PD	228 ± 9	259 ± 5	261 ± 5	262 ± 5
	High PD	237 ± 3	268 ± 2	269 ± 2	271 ± 3
	P	0.370	**0.020**	0.057	0.138
Cumulative latex	Lowland	43 ± 1	48 ± 1	47 ± 2	46 ± 2
(Mg ha^{-1})	Highland	35 ± 2	50 ± 2	51 ± 2	53 ± 2
	P	**0.003**	0.423	0.175	**0.018**
	Low PD	50 ± 1	59 ± 1	59 ± 1	58 ± 1
	Medium PD	44 ± 3	53 ± 2	53 ± 2	53 ± 2
	High PD	38 ± 1	46 ± 1	46 ± 1	46 ± 1
	P	**0.001**	**<0.001**	**<0.001**	**<0.001**

If biomass and latex yield were expressed per ha (plot level estimates), lowland rubber plantations benefited less from future climate change (Figure 4.12 a,c). TB and $Latex_{cum}$ of lowland rubber plantations modelled from baseline to RCP 8.5 increased by 8% and 7%, respectively, with an increase up to RCP2.6 followed by a slight drop to RCP 8.5. Total biomass of highland rubber plantations increased by 28% under the same modelling scenarios, and showing an increase of 51% in $Latex_{cum}$ (Table 4.5). The ANOVA test showed significant differences between highland and lowland rubber plantation TB and $Latex_{cum}$ for baseline and climate change scenarios up to RCP 8.5. Denser rubber plantations had larger TB, but lower cumulative latex production (Figure 4.12 b, d). The most significant difference in TB among various planting densities was found for RCP 2.6, if LSDs were compared. However, there was no

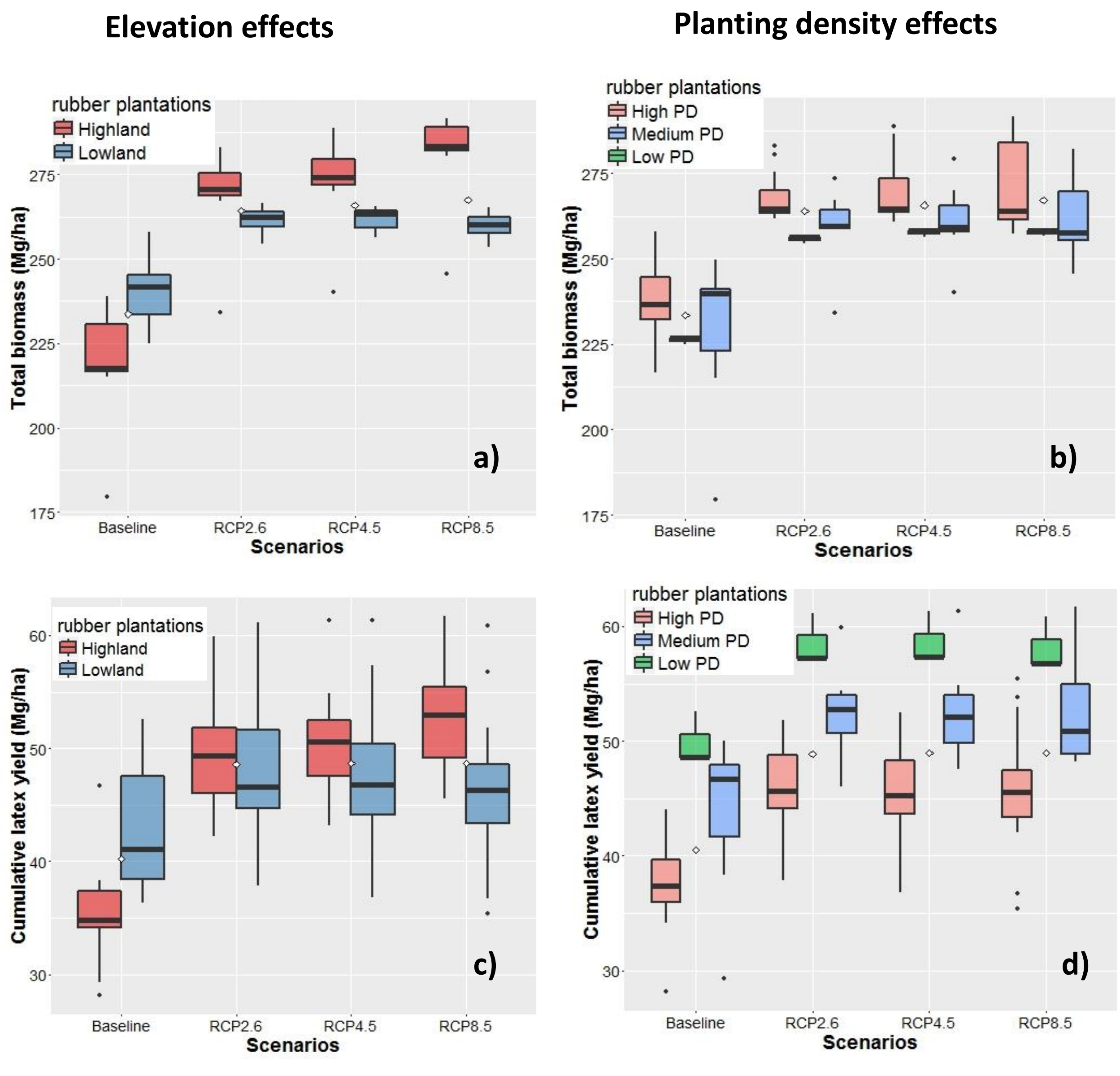

Figure 4.12. Total plant biomass (a, b) and cumulative latex yield (c, d) per plot predicted by LUCIA (40-year rotation). Highland and lowland rubber plantations' and various planting density design (low-, medium- and high planting density) are compared under baseline, RCP2.6, RCP4.5 and RCP8.5 climate scenarios.

significant TB variance detected for baseline, RCP 4.5 and RCP 8.5. In addition, different planting densities showed significant different impacts on $Latex_{cum}$ across climate change scenarios.

4.4 Discussion

4.4.1 Latex productivity and carbon sequestration potential as affected by management

Our observed and simulated results revealed that expanding rubber plantation into higher marginal areas negatively affected rubber performance. In particular, latex yield was more affected by colder temperatures at higher elevations than tree growth. At higher elevations model predictions revealed a significant delay in reaching a tappable DBH (16 cm) up to 10 years at 920 m.a.s.l. This delay increases the risk that farmers start tapping too early under economic pressure.

Rubber plantations in the highlands had lower numbers of new flushes and shedded leaves earlier than in the lowlands, which resulted in a relatively shorter photosynthetic period for carbon accumulation (Meti et al., 2014). In addition, Nguyen et al. (2013) explored the changing of latex productivity along elevation gradients (15 - 738m a.s.l.) and density ranges (173 - 480 tree ha^{-1}) in Vietnam. They concluded that latex production would suffer from a rapid drop of productivity when planted beyond a certain elevation level (> 500 m a.s.l.), and latex yield per ha was positively linked with stand density (stand age 1-20 years). However, the results of such studies cannot be directly transferred to other rubber cultivation regions with different site-specific conditions; for example, to plantations located higher than 800 m and/or with planting densities > 500 tree ha^{-1}. In Xishuangbanna, elevation effects have been explored with regards to rubber tree biomass accumulation (Song and Zhang, 2010) and latex yield (Yi et al., 2014b). It was concluded that rubber plantations lose their carbon sequestration and latex production potential when located at higher elevations and denser tree stands (Yi et al., 2014a). However, those studies were based on empirical models describing the statistical relationships rather than the ecological processes. Such relationships are hardly transferable to new objects or conditions because they rely on fixed parameters optimized for a given environment. In addition, these studies also partly depend on stand age of surveyed rubber plantations. Old-aged rubber plantations tend to have higher carbon sequestration potential but are located more in lowlands (Yang et al., 2016). By contrast, process-based models like LUCIA, applied in the current study, offered significant advantages for increasing our understanding and predicting forest behavior at tree, stand, and landscape level (Korzukhin et al., 1996). We compared results of our biophysical simulation with data gathered during smallholder interviews in the region (Min et al., 2017), plotting annual latex production versus elevation gradient (621 - 1127m a.s.l., Figure 4.13a, c) or planting density (360 - 900 trees ha^{-1}, Figure 4.13b, d).

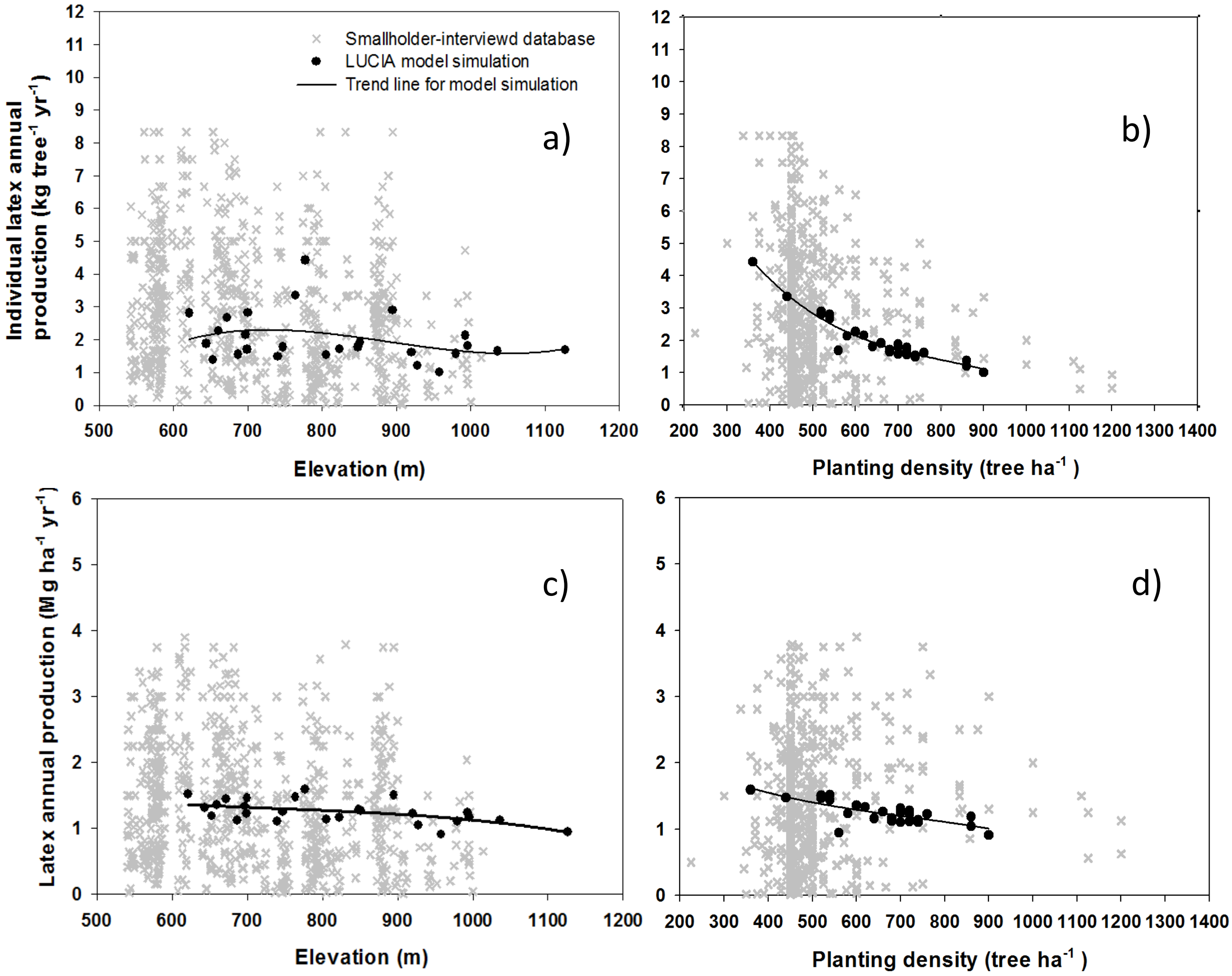

Figure 4.13. Annual latex production along elevation and planting density gradients. shown at individual tree level (a, b) and plantation level (c, d), respectively. Sample size for LUCIA simulation was 27. The grey crosses represent mean annual latex yield with corresponding elevation as obtained from a smallholder interview database (Min et al., 2017a).

Our simulations of rubber performance furthermore revealed an even stronger effect of planting density than elevation, i.e. increasing planting density to high values observed in the field (740 trees ha^{-1}) reduced annual latex production by up to 15% (compared with state-farm advised density with 495 trees ha^{-1}). The lowest plating density observed in our dataset (360 trees ha^{-1}) provided the highest latex yield. Higher planting density increases competition between trees for light, nutrients in the soil and possibly water use efficiency (Fearnside, 1995; Nguyen, 2013) particularly once the crown canopy is closing. This will further affect rubber leaves intercepted photosynthetically active radiation, then determine tree biomass development. LUCIA realistically represented this trend due to the newly developed plantation module representing the physiological changes from individual tree level to even-aged plantation level. A process-based model LUCIA simulates the hierarchy in preference of assimilated carbohydrate allocation by various tree organs: leaves development > branches growth and stems development > roots system. The daily latex generation in LUCIA depends on resource allocation to stem biomass (Figure 4.4), which was a major part of aboveground biomass. Simulated stem biomass decreased with increased elevation both at tree and plot level (Figure S4.4a). With increasing planting density, individual tree stem biomass growth showed a sharp decline from 14 to 5 kg $tree^{-1}$ yr^{-1}; though, it contributed slightly positive to plot level stem biomass increase due to a higher tree number (Figure S4.4b). In the context of the Naban Nature Reserve, the optimum biomass and latex yield for smallholder rubber farms could be found at an elevation < 800 m a.s.l., for plantations with a planting density < 600 trees ha^{-1}, based on model simulations. Denser plantations located at higher elevations had a high total biomass, but suffered from a decrease in stem biomass at plot level and a concomitant decrease in cumulative latex production (Yang et al., 2017). Roy et al. (2005) and Nguyen (2013), confirmed the importance of the effects of planting density at both the individual tree and plot level. They reported that annual latex production per tree decreased along density gradients from 200 to 500 trees ha^{-1}, while results expressed per ha showed an increasing trend. The latter trend found by those authors appears at first view opposite to our model simulation (Figure 4.13 d). This was mainly due to the relatively high tree density in our study region that resulted in clearly delayed tapping due to the slower developing DBH in denser stands. According to the smallholder interview database from Min et al. (2017), the maximum tree density observed was 1200 tree ha^{-1}, around 2.4 times the recommended state-farm planting density of 495 tree ha^{-1} (Yi et al., 2014a). Moreover, our study region was located in a high elevation mountainous area; therefore, increasing planting density could not compensate the declining production in low-profit rubber plantations.

4.4.2 Trade-offs between biomass development and latex production under climate change

Our simulations revealed that a future warming of the climate turned the currently unfavorable environment at high elevation regions into a more suitable habitat for rubber. This is consistent with other projected rubber distribution modelling results (Zomer et al., 2014; Ahrends et al., 2015). The effect of elevation on rubber growth and latex production was simulated by LUCIA with 0.6℃ air temperature decline for every 100 m increase in elevation (Marohn and Cadisch, 2011), based on experimental observations (Dijkman 1951; Moraes 1977). Plantations cultivated at lower elevations already had optimum temperatures for rubber photosynthesis; while current temperatures at higher elevations were lower than optimal (27 - 33°C). Most studies concluded that natural latex production showed an inverse correlation with temperature, within the range 23.5- 37.8℃; Rao et al., 1998; Raj et al., 2005; Kositsup et al., 2009; Yu et al., 2014; Golbon et al., 2015; Nguyen and Dang, 2016). The lowland rubber plantations (< 900m a.s.l.) in our simulation (Figure 4.12c) responded to future global warming by 1.6 - 2.4°C inconsistently, with no significant changes. However, highland rubber plantations had a significantly higher biomass and latex production in simulated warming scenarios. It is worth noting that highland rubber plantations could also exhibit a negative response towards future warming, with the possibility of unsimulated stresses and extreme events (Nguyen, 2013). Generally, rubber has low productivity in hot and drought-prone areas, which could be a scenario under a warming climate (Satheesh and Jacob, 2011). The expansion of extremely hot area in 2050 (MAT about 22℃; MAP about 1383 mm yr^{-1}) indicated the drier condition in lower elevation regions (574-893m), this would turn these area into unsuitable habitat. The high elevation regions (978-2014m) had lower temperature (MAT about 18℃) but more rainfall (MAP about 1567 mm yr^{-1}) (Zomer et al., 2014). Chantuma et al. (2009) interpreted this low production as a result of shifting carbon allocation to non-structural carbohydrate (NSC) reserves, at the expense of growth and latex yield, to cover the risk of increased carbon loss induced by tapping. According to our model predictions, rubber growth and latex production would not be limited by modified environmental conditions at higher elevation, even though higher planting density would cause rapid decline of total biomass and latex yield for individual trees (Figure S4.3). To meet livelihood requirements of smallholder rubber farmers, and maintain optimum carbon stocks, low to medium planting densities (495-600 trees ha^{-1}) would be advisable (Figure 4.12).

4.4.3 Limittations of study and implications for future investigations of rubber-based systems

The increase of CO_2 in the atmosphere could lead to increased plant productivity where growth is not limited by other factors such as soil fertility or water availability (Hyvönen et al., 2007; Ainsworth and Long, 2005). However, process-based models do not always include CO_2 enrichment effects for different climate change scenarios. For this study, future climate change was represented by simulation of changes in daily precipitation and temperature, rather than modelling direct effects on assimilation rates. For baseline modelling, we considered other environmental factors affecting plant growth such as soil temperature and solar radiation (Yeang, 2007; Borchert et al., 2015). Those factors were not considered in other crop models like CROPWAT (Allen et al., 1998) and WaNuLCAS (Van Noordwijk and Lusiana, 1999).

We noticed that the simulated leaf shading pattern was delayed when compared with observed data. The mechanisms causing leaf shading and flushing are still under debate, therefore in the current LUCIA version these phenological phenomena were represented in a relatively simple way, mainly driven by water and temperature limitation during dry season. Generally, the leaf fall in deciduous species occurs in the dry season because of a depletion of water stored in the tree (Reich and Borchert 1984; Borchert 1994; Reich 1995). When the canopy is reduced or absent for a sufficient time, stems rehydrate and leaf flush can be initiated. This could explain why leaf flush is frequently initiated prior to rains (Duff et al., 1997). In addition, Lemos-Filho et al. (1993) found that rubber tree leaf flushing requires the minimum base temperature to be approximately 16℃ with 420 degree days for successive initiation. They confirmed the applicability of the heat-sum model for rubber bud growth, and improved model fitting by adding day length as an exponential term in accumulated degree days (Lemos-Filho et al., 1997). This demonstrated that further model improvement in LAI simulation can be done by additional consideration of day length.

LAI dynamics of mid-aged rubber plantations was relatively well predicted in our study, while LAI in young- and old-aged plantations tended to be under-estimated from June to December. The site-specific conditions might play an important role in canopy development. In our study young rubber was located on very steep slopes where tree growth was constrained by both weeds and higher erosion, while old-rubber plantations had more dead trees and falling branches. Increasing the number and hence variety of permanent sample plots for long-term monitoring could help to provide more sophisticated model parameters. A function describing tree mortality and decrease in tree density with plantation age could be another option for model improvement.

According to the latex generation function used in previous model WaNuLCAS (Van Noordwijk and Lusiana, 1999), resources for latex go directly from the growth reserve pool to the pool available for tapping. However, the growth reserve pool was not, as yet, included in LUCIA for the sake of simplicity. However, this process simplification might lead to an delay of initiation of growth and latex production after stress periods. Further model improvement could be done by inclusion of diurnal temperature changes instead of mean daily temperatures used at present. This would provide a more precise description of latex production and latex flow across the full 24 hours of a day (Yu et al., 2014).

In order to better understand elevation and planting density impacts, we simplified our model to assume that rubber plantations were free of extreme events and nutrient stress. This could represent another area where changes could be made in climate change modelling. The dominant rubber clones planted in the study region are GT1 and RRIM 600, similar to those of other regions of Xishuangbanna (Yi et al., 2014b). Clone GT1 can resist cold stress and diseases, but gives lower yield of latex (Luo et al., 2012), while RRIM 600 provides a higher latex yield, but is sensitive to cold stress and diseases (Priyadarshan et al., 2005). The newly developed clone type

Yunyan77-4, which shows better resistance to low temperatures and is currently often planted at higher elevations occurs in the study site as well (Chen et al., 2008). For simulation we used input data averaged across different rubber clones. Using data detailing clone-specific responses to climate change would be of interest in future studies For example, Nguyen and Dang (2016) reported a different temperature dependence with 2 dominant clone types (GT1 and PB235) in Vietnam, and were able to identify important clone and soil considerations for latex yield prediction.

Although process-based models still have limitations, they are increasingly being applied in projections of forest growth and productivity under climate change, and are serving as decision making tools. Previously published forest models have not included detailed simulation of latex production, which makes relevant management guidance difficult. In contrast to established empirical models, our spatially explicit model is capable to continuously simulate rubber tree growth and productivity using data from intensive ground surveys. Thus, it could be used in other rubber cultivating regions with updated input data on local climatic and soil conditions. Consideration of such factors as land use and land cover, soil properties, local climate, regional market forces, agricultural management strategies and coherent traditional wisdom from local farmers could help to generate customized adaptive strategies (Reidsma et al., 2010; Tripathi and Singh, 2013). Few studies have explored climate change impacts on rubber-based systems, and corresponding adaption and mitigation strategies are still incomplete (Chantuma et al., 2012). Considering that rubber growth and latex production are vulnerable to cold, future adaptation strategies should include the improvement of rubber tree environmental resistance. This could be done by cautious genotype selection for traits such as wind/cold resistance and yield (Priyadarshan et al., 2005; Luo et al., 2012). The upscaling of modelling results to larger areas, with consideration of the ecological and socio-economic importance of rubber management, could effectively support regional decision making. These efforts could also contribute in a wider context to global climate change adaptation and mitigation for rubber-based systems.

4.5 Conclusions

Against a background of global climate change, the impact of different elevations and planting density on biomass development and latex production in Pará rubber was examined under present and projected future climate scenarios. Using process-based modelling, we simulated rubber growth and latex production at tree, plot and landscape level. This is the first report of such modelling for cultivation regions higher than 800 m a.s.l. and planting densities > 500 tree ha^{-1}; extending the research and evaluation to new rubber expansion regions in Xishuangbanna, China. Under current climatic conditions, the optimum ranges for rubber cultivation were determined at elevation < 900 m a.s.l. and planting density < 600 trees ha^{-1}. Under future climate change scenarios, high elevation are favorable for rubber growth, owing to warmer conditions and increased precipitation (13% higher than at elevation < 900m). According to simulations, rubber biomass development and latex production would not be limited by modified environmental conditions at higher elevation; while higher planting density had negative impact on tree biomass. To meet the local livelihood requirement and improve regional carbon sequestration potential, low (< 495 trees ha^{-1}) and medium planting densities (495 - 600 trees ha^{-1}) would be advisable. Moreover, global climate change scenarios projected on a regional context, might fail to reflect the influence of temperature and precipitation, owing to a relatively strong management impact on aspects such as planting density. Integrated with an intensive ground survey, our spatially explicit model proved its capability of continuous simulation of rubber growth and productivity during the whole rotation. The model could be applied in other rubber cultivating regions using local input data on climate and site conditions. This could facilitate regional sustainable rubber management, and contribute to global climate change mitigation efforts.

4.6 Supplement

Table S4.1 Artificial watershed model run times. Here list combinations of elevation and planting density classes to cover full ranges of surveyed plots (n = 27). Model had run seven times with 40-year length to complete baseline simulation. Note: there were some plots with same elevation and planting density class.

LUCIA test points	Elevation classes	planting density	Elevation included	Plot No.
1	500	NA	500	0
2	600	540, 700, 860	650	3
3	700	520, 540, 600, 620, 700, 720, 740	700, 750	8
4	800	360, 440, 660, 680, 720, 740	800, 850	7
5	900	520, 760, 860	900, 950	3
6	1000	580, 680, 700, 900	1000, 1050	4
7	1100	560, 640	1100	2

Figure S4.1 Litter accumulation from litter traps (n=9 for each plot) and leaf area index measurement by SUNSCAN in: a) young rubber plantation, b) mid-aged rubber plantation, c) old-aged rubber plantation. The Beam Fraction sensor of SUNSCAN was demonstrated in d).

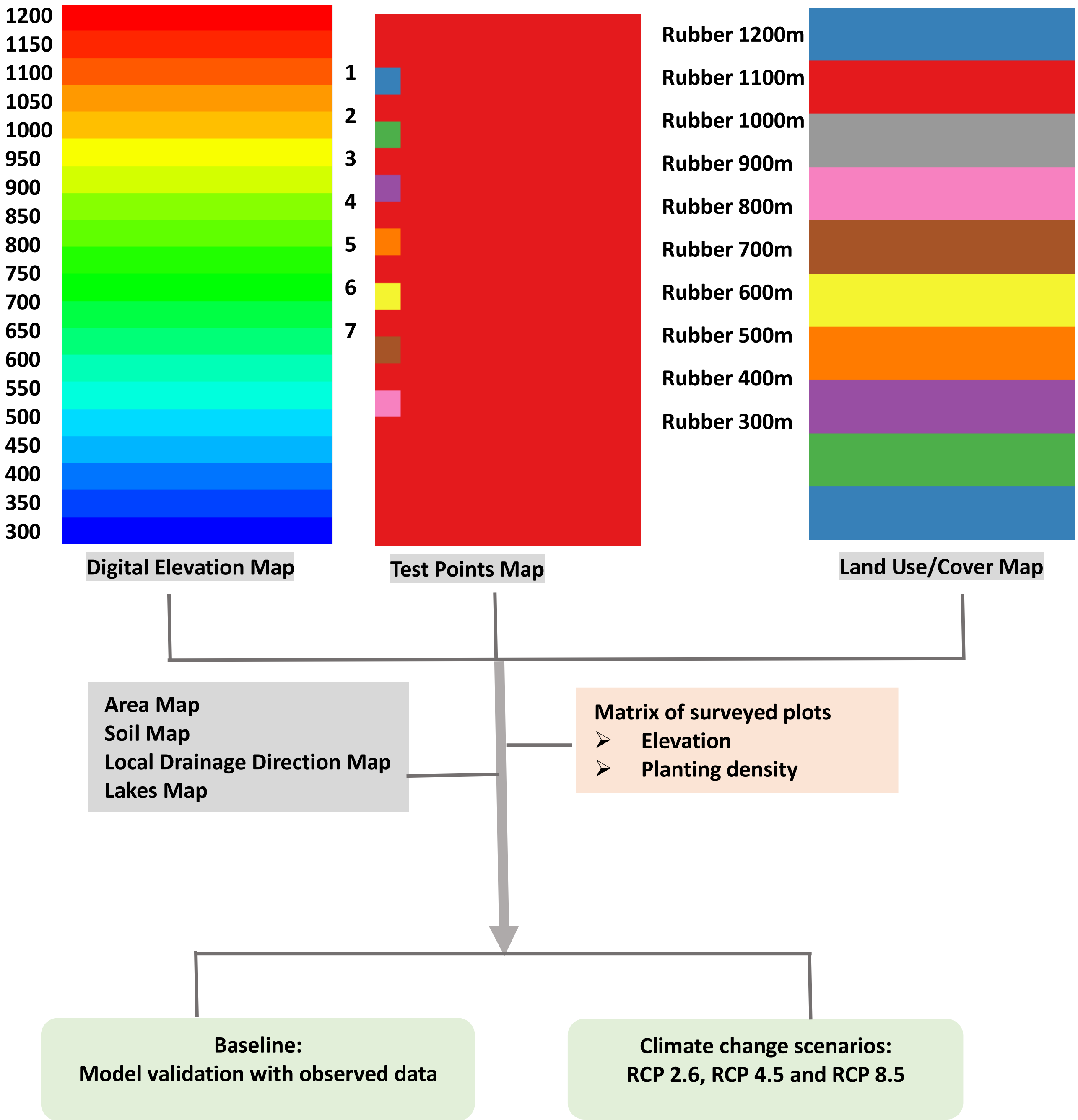

Figure S4.2 Artificial watershed modelling procedures illustration. The test points were selected among 500-1200 m to represent whole landscape rubber distribution altitude ranges.

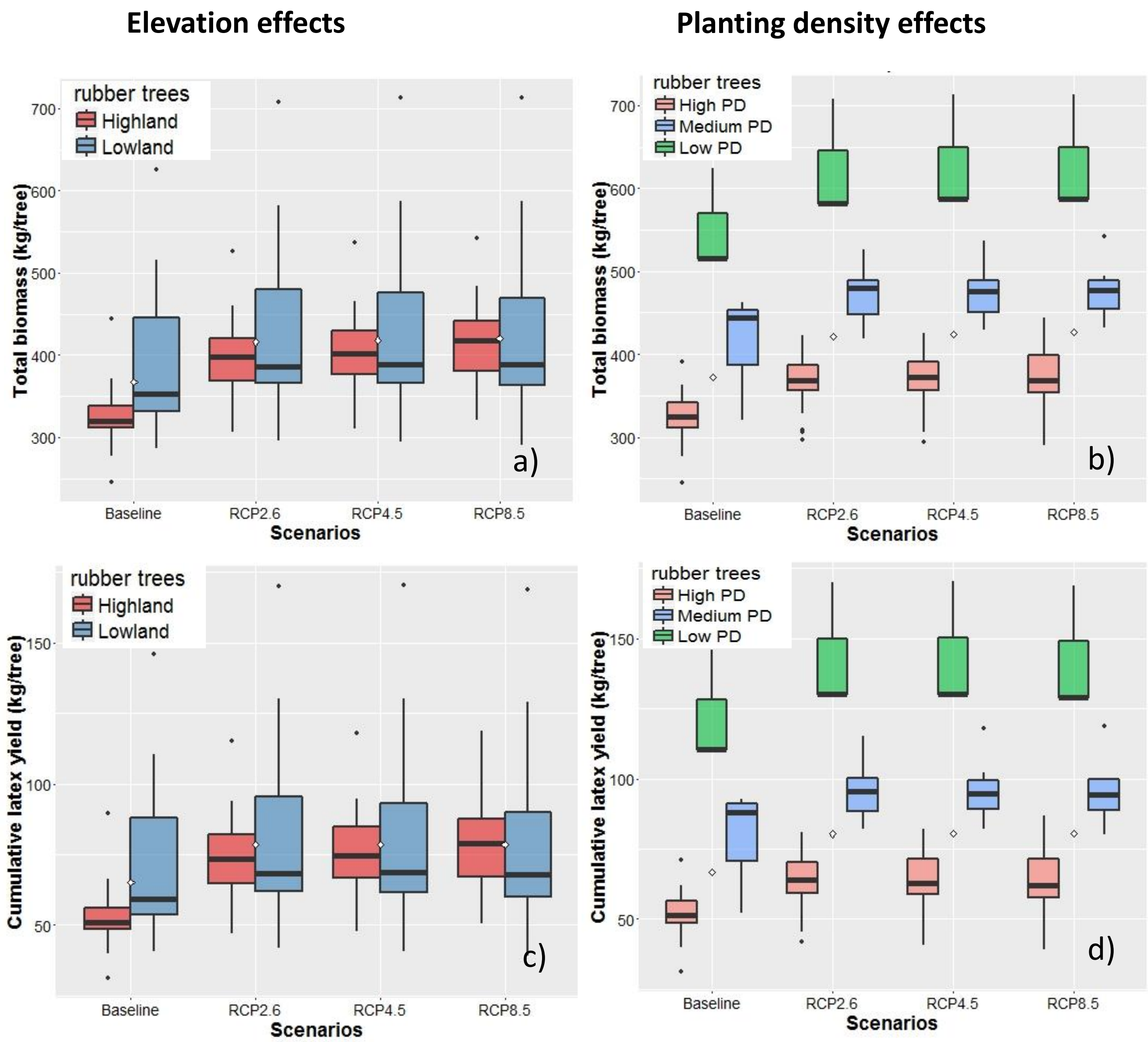

Figure S4.3. Total plant biomass (a, b) and cumulative latex yield (c, d) per tree predicted by modeling (40-year rotation). Highland and lowland rubber plantations' and various planting density design (low-, medium- and high planting density) are compared under baseline, RCP2.6, RCP4.5 and RCP8.5 climate scenarios.

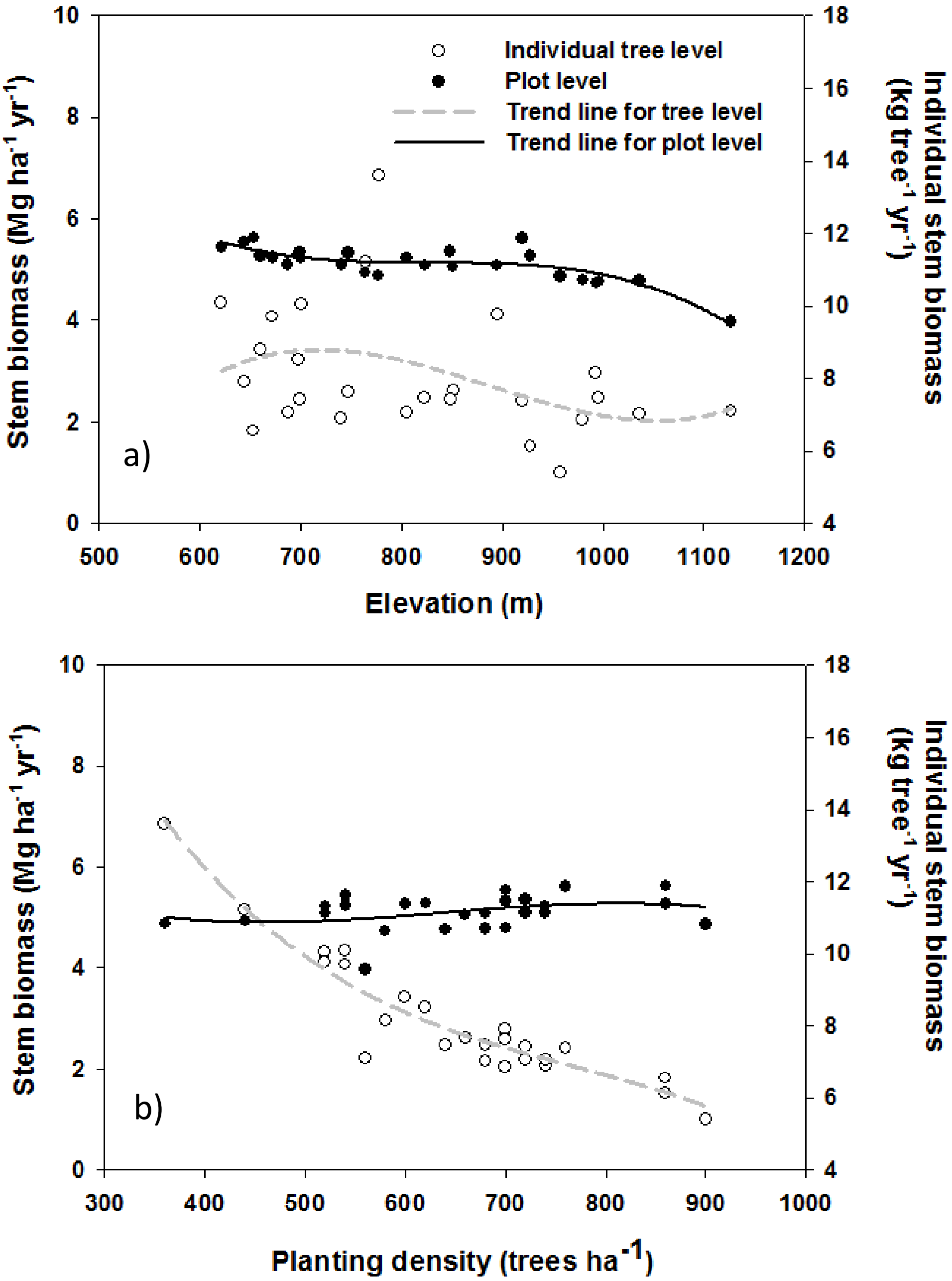

Figure S4.4 Stem biomass development along a) elevation and b) planting density gradients at tree and plot levels.

Chapter 5

General Discussion

Chapter 5 General discussion

5.1 Carbon stock evaluations of rubber based systems: challenges and opportunities

As one emerging important land use type in South East Asia, rubber plantations still keep expanding even under the decreased global market price. The accompanying concern regarding the impacts on regional ecosystem services and benefits is still a hot topic. The carbon stock evaluation approaches differ with various research aims, therefore making comparisons among various land use types challenging. In this way, a cost-effective and widely applicable carbon accounting approach is useful (Chapter 2). Most rubber cultivated regions are lacking existing site specific allometric equations for rubber biomass evaluation, therefore the generic forest allometric equations would be used. This will cause over-estimation of tree biomass even with species-specific wood density. The reason was owing to the constrained tree trunk developing because of tapping activities, as discussed in Chapter 3. Therefore, it is important to adapt generic allometric equations with consideration of both bio-climatic conditions and regional management (planting density) effects. Rubber plantation establishment are affected by land use change, climate change and local management effects. It is difficult to simultaneously simulate all impacts, however, a good understanding of integrative effects is essential for proper decision making. The attempt to evaluate rubber plantations growth and latex yield under climate change were carried out for marginal expansion regions, and the regional management strategies (cultivation elevation, planting density) were discussed (Chapter 4). In this chapter, we will further explore the potential for increasing carbon sequestration of rubber-based systems in marginal areas.

5.2 Scaling issues in forest management and decision making

Scaling is defined as a change in grain and/or extent with regard to the temporal and/or spatial representation of the system (O'Neill, 1989). It is widely recognized as a central and crucial issue in ecology. However, scaling issues have received comparatively little attention in the forest community, who are responsible for sustainable management, including researchers, model developers and forest practitioners (Seidl et al., 2013). Scaling considers great variability in space and time, and the nonlinear interactions between processes across scales (Green and Sadedin, 2005). An approach frequently applied to cope with these complexities is simulation modelling. Models serve as vehicles for scaling and extrapolation, they translate our conceptual understanding about ecosystem functioning and structure into formal computer code, allowing for a quantitative analysis of its drivers and behaviors (Seidl et al., 2012).

In the present study, rubber-based system carbon sequestration under climate change, can address heterogeneity and asymmetry in the context of providing information on carbon for management decision making. The varieties of spatial and temporal scales were reported in Table 5.1. Making appropriate usage of scales when solving various research questions is significant for forest management. For instance, the challerges of measurement of leaf area index for rubber-based system were intensively discussed in Cotter et al. (2017). We can derive the stand leaf area from knowing the average area of a leaf and the number of leaves in the stand (linear scaling), but we cannot in analogy derive the light absorbed by the canopy via absorption of the average leaf (nonlinear scaling). Considering the relationship between radiation interception and primary productivity is highly nonlinear at hourly to daily time scales, it scales linearly at monthly time scales (Medlyn et al., 2003). This is harnessed in widely applied forest production models. Owing to empirical models are designed to describe forest growth over time, such as allometric equations used in Chapter 2 and Chapter 3, they focus on a single ecosystem compartment, stems, leaves, or roots. They are not sufficient to represent the forest carbon cycle and fulfil the information needs of managing for climate change mitigation. They contain the inability to track changes in soil, litter and deadwood carbon pools (Seidl et al., 2013). Eco-physiological process models can combine data and process understanding from many different scales

(Fontes et al., 2010), and these processes have been scaled to the stand (Cienciala and Tatarinov, 2006), national (Lagergren et al., 2006), continental (VEMAP Members 1995) and even up to the global scale (Running and Hunt, 1993). In addition, to account for the contribution of individual rubber trees to the landscape-scale carbon exchange, it is useful to consider them explicitly rather than assuming average conditions (Chapter 4). Therefore, it is important to choose an appropriate scale to capture the heterogeneity in the landscape, allowing better understanding of ecosystem flux dynamics and carbon storage in forests over larger areas (Hasenauer et al., 2012).

Table 5.1 Scaling involved in the preceding chapters.

Spatial scale	Temporal scale	Methods	Chapter
Tree-level	annual	1) Existing allometric equations	2
	annual	2) Establishing allometric equations from harvested trees	3
	daily	3) Process-based modelling	4
Plot-level	annual	1) Upscaling from tree-level	2,3
	daily	2) Plantation mode from LUCIA modelling	4
Landscape-level	annual	1) Upscaling from time-averaged C stock	2
	daily	2) Spatial explicit modelling with regional land use, climatic and soil input.	4

5.3 How to deal with uncertainties during decision making in rubber-based system?

Quantifying uncertainty more rigorously represents a powerful step for strengthening the ecological sciences (Yanai et al., 2010). The knowledge about potential climate change impacts on rubber plantations distribution (Zomer et al., 2014; Ahrends et al., 2015), latex production (Rao et al., 1998; Raj et al., 2005; Nguyen and Dang, 2016), carbon stock (Yang et al., 2017) is continuously expanding. The potential impact from extreme events have been observed (Ahrends et al., 2015). However, it is still challenging to advise land use decision makers on planning for climate change impacts. Many uncertainties and unknowns remain and it is difficult to communicate these to practitioners and other decision makers while retaining emphasis on the importance of planning for adaption (Keenan, 2015).

Reyer (2013) proposed a typical modelling chain for climate change impact studies (Figure 5.2). It is important to note that all three aspects of uncertainty (model structure, input and parameters) at each step of the model chain contain different levels of uncertainty. These uncertainties contain measuring-, statistical-, and scenarios uncertainties (Walker et al., 2003). Communication of climate change projections and impacts and the related uncertainties to non-scientific audience is an important contributor towards facilitating adaption. Recent research (Blennow et al., 2012; Yousefpour et al., 2013) has found that forest managers' beliefs about climate change influences their decisions. The effective communication of uncertainties to

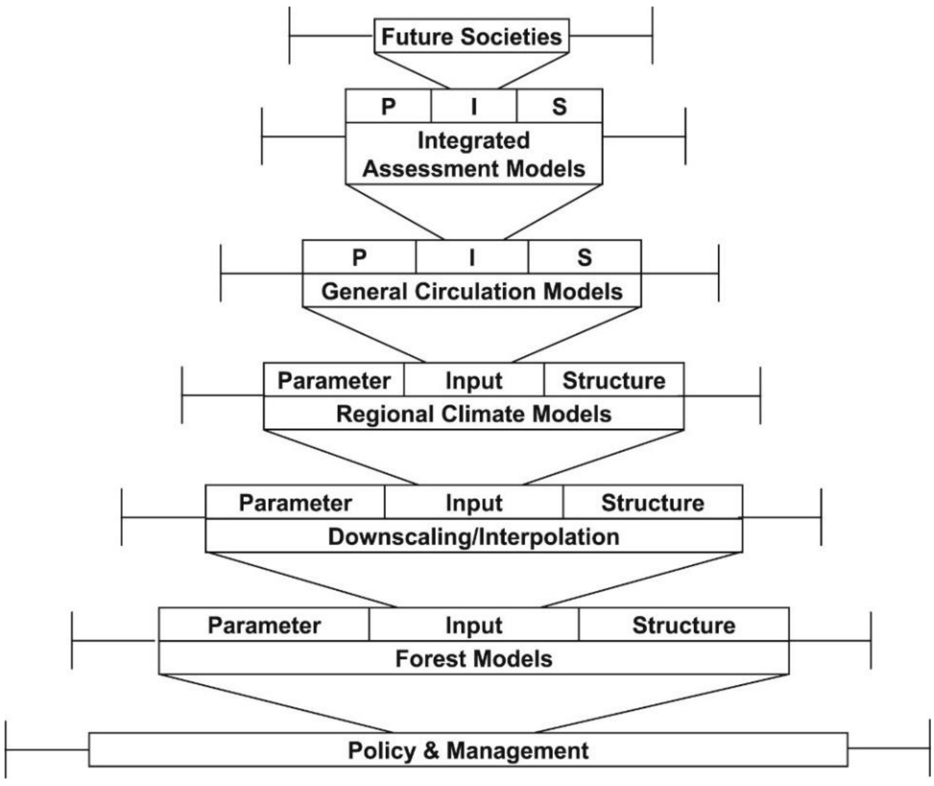

Fig. 5.1. The Cascade of uncertainty. The upper boxes of each compartment represent

three locations of uncertainties common to every step of the cascade and the stylized error bars the range of uncertainty (Reyer, 2013).

policy makers should be brief and simple to understand. The decisions should be solidly based on detailed knowledge about probable outcomes of climate change for forests (Yousefpour et al., 2012). Existing studies yield differing and sometimes conflicting results when projecting latex yield under climate change. For example, an inverse relationship with temperature rise (ranging from 23.5 to 37.8°C) was detected in other rubber-cultivated regions (Rao et al., 1998; Raj et al., 2005; Kositsup et al., 2009; Nguyen and Dang, 2016). They also raised concerns for more negative impacts towards highland rubber plantations. This was consistent with our lowland rubber plantations prediction, while our highland rubber plantations showed a positive relationship with global warming (Chapter 4). The discrepancy result from: 1) those results derived from various models (empirical, process-based or hybrid), the algorithms used for latex estimation were different; 2) the site-specific environmental conditions might be different from global projected climatic impacts; 3) the clone-types of rubber contain different environmental tolerance; 4) the consideration of extreme events and environmental disturbance or not. In addition to this, the uncertainties considered in our tree level (Chapter 3) and plot level (Chapter 2) carbon stock evaluation, could provide further reference for evaluations of acceptable prediction errors.

5.4 Added-value from stakeholder's knowledge for sustainable rubber cultivation

Nabanhe nature reserve has three principles: the unchanged forest land tenure, the stable administrative boundary and the permission of local residents to live inside the nature reserve. This is a unique forest management and conservation strategy which calls for harmony between humans and the natural environment. Before the official establishment of the nature reserve, forests were easily influenced by human activities, such as traditional slash and burn activities for shifting land cultivation, or exchanging forest land into cash plantation crops. In addition, the establishment of power stations also decreased forest land, agricultural crops, bush and grassland nearby to the riverside (Tao. 1989). Mo et al. (2011) reported how different traditional forest management systems impact on forest biodiversity and composition. They found a good potential of forest regeneration if in close proximity to undisturbed forests, which serve as a seed source. However, these traditional forest use systems are under threat from expanding mono-culture rubber plantations. The Chinese-German project SURUMER (Sustainable rubber cultivation in the Mekong region) served as a case study with the aim of developing sustainable land use strategies for rubber cultivation in southwest China. The participation of dominant stakeholder groups, such as scientists, farmers and village heads, regional decision makers, as well as provincial and national actors contributed to establish efficient communication channels and thus a holistic information exchange (Wang et al., 2018). The indigenous knowledge of stakeholders contributed to obtaining project priori information, concerning historic land use types, soil condition and local management (Chapter 2 and Chapter 3). With the support from the SURUMER stakeholder conference, modelling results could be transferred into guiding regional land use policy making. The advised planting density in marginal area was discussed, and integration with climate change impacts were reported (Chapter 4). Besides this, more ecosystem services like water yield, sediment retention, and habitat suitability in landscape were evaluated by modelling tools. Results showed that inclusion of stakeholder groups was critical for proper evaluation of ecosystem services. This was due to the fact that integrated ecosystem services' indices were generally overestimated when using equally weighted ecosystem services results (Thellmann et al., 2017). These insights will further benefit forest resource management, and realizing the final goal of this man and biosphere reserve- to make a harmonious relationship between human and nature come true.

5.5 Adaption of rubber-based system adaption to climate change

Plantation crops such as rubber, tea and coconut typically require a lengthy life cycle, accompanying with considerable capital investment. This greatly constrains options for climate change adaption when compared with annual crops (Lobell et al., 2007; Lobell and Field, 2011). Moreover, there is still a research gap to empirically investigate the drivers of adaption choice in perennial agriculture (Gunathilaka et al., 2017). Rubber as an example of a perennial crop with an economic life span of about 25-40 years, contributes to regional revenue and livelihood improvement in South East Asian countries (Yi et al., 2014a). We explored the environmental factors which drive rubber tree carbon stock and latex yield at landscape level (Chapter 3 and Chapter 4), or based on estimations of major predictive factors for soil organic carbon stock distribution mapping in this mountainous subtropical landscape (Laub et al., 2018). We further estimated the response of rubber plantations to future climate change (Chapter 4). For the rubber dominated agricultural landscape, we also evaluated other land use types' carbon sequestration potential from historic until present conditions (Chapter 2). However, to provide a comprehensive evaluation of climate change response, mitigation and adaption options, the trade-offs between land use options and diverging interests of multiple stakeholders are an open issue.

The climate change adaption programs are focused on agriculture with higher production but with fewer inputs. The request for more adaptive agriculture is significant for coping with future environmental stresses and increasing trend of agricultural intensification (Jones et al., 2012). There are many existing approaches to achieve this goal:

1) Sustainable intensification: this system is aiming to increase production from existing farmland while minimizing pressure on the environment (Perfecto and Vandermeer, 2010). In order to cope with negative impacts from rubber cultivation, more diversified rubber plantations' cultivation is widely encouraged in Xishuangbanna (Wu et al., 2001; Zhang et al., 2007; Pang et al., 2009). Promoting rubber-intercropping systems could serve as an efficient way for improving micro-climate and increasing carbon sequestration potential for the whole landscape (Langenberger et al., 2017).

2) Climate-smart agriculture (CSA): this system aims to achieve the "triple wins" of food security, adaption and mitigation (FAO, 2013). It enhances adaptation and mitigation synergistically. Villamor et al. (2014) applied an agent based model to explore the potential of payment for ecosystem service (PES) design under rubber eco-certification scheme. The ecosystem service trade-offs were discussed based on household agents. The results demonstrated that land-use practices such as rubber agroforests, if integrated with an appropriate management scheme or incentive (e.g. PES), could reduce carbon emissions while improve local livelihood.
3) Climate-smart landscape (CSL): this approach is an integrated, landscape-level method that considers both adaption and mitigation objectives, as well as other aspects from food security and livelihood improvement (Sayer et al., 2013). It widens the scope from the farm level to landscape level, providing analyses of landscape dynamics that lead to various trade-off analyse (Salvini et al., 2016).

In the context of rubber-based system, there are many efforts to promote biodiversity conservation in the landscape level, while fulfilling local people's requirement for latex yield and agricultural production (Thellmann et al., 2017). Moreover, the landscape evaluation provides spatial reference for establishing feasible carbon trading markets, or payment for ecosystem services for rubber-based systems (Yi et al., 2014b). More efforts could be spent to select appropriate clone types and conduct agroforestry under future climate change conditions, this could be achieved by ecological niche modelling (Ranjitkar et al., 2016). It contributes to benefit farmers and enhancing environmental conservation and restoration for future climate adaption

5.6 Implications for rubber diseases prevention and yield improvement in mountainous area

Rubber cultivation in non-traditional regions with colder and dryer climate conditions could result in changes in rubber phenology (Priyadarshan, 2017). Rubber trees in Xishuangbanna showed prolonged periods of defoliation and refoliation due to diminished temperature in the dry season (Yunnan Institute of Tropical Crops, 1981). Many studies reported that decreasing of temperature in high elevation area would advance the phenology of rubber plantation around 3-12 days (Jia, 2006: Meti et al., 2014). Rubber phenology is sensitive to ambient climatic conditions (Zhai et al., 2018), it links closely with latex yield (Meti et al., 2014; Yu et al., 2014) and has high correlation with powerdery mildew disease (*Oidum heveae*) (Shao and Hu, 1984; Shao et al., 1996; Xiao, 2010). Against a global warming background, the long-term effects from rubber cultivation at higher elevations could be well understood based on process-based modelling (Chapter 4). In addition, elevation linked to various seasonal arrangements of rubber trees life cycle events (Phenophase) is important for effective diseases prevention and latex tapping (Figure 5.2). At high elevation rubber trees showed early wintering and refoliation. Severe leaf fall disease and low temperature put rubber in these regions under more pressure. Moreover, the altitudinal related changes in climatic conditions, litter decomposition rate and soil nutrient dynamics also contributed to rubber phenology and latex production changes (Meti et al., 2014). The corresponding bio-climatic stress index, which was discussed in Chapter 3 also reported different tree biomass of low-elevations in tradtional growth regions (e.g. Malaysia, Brazil), up to high elevation mountainous area in China. Mountainous regions serve as habitat to about half of the world's biodiversity hotspots, how climate change will affect this important global heritage is still site-specific and subject to debate (Kohler et al., 2014). There still needs to be more efforts and future studies for mountainous regions, to provide the chance to link with other rubber-cultivated regions for guiding effective management.

5.7 Concluding remarks and final recommendations

Constrained by geographic locations, budget, and time availability, many existing studies face data-limitation issues. Besides this, individual knowledge gaps exist in predicting forest productivity responses to climate change. Therefore, selecting proper modelling tools could serve as a surrogate for forest response simulation, and further

Elevation	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
0-100m	Flowering	Fruit growth	New flush	Flowering	New flush				New flush		Wintering	New flush
100-300m	Flowering	Fruit growth	New flush	Flowering	New flush				New flush		Wintering	New flush
300-432m	Flowering		New flush	Flowering		New flush				Wintering	New flush	Flowering
550-600m	New flush	Flowering	New flush				Fruiting			Wintering	New flush	Flowering
750-800m	New flush	Flowering	New flush				Fruiting			Wintering	New flush	Flowering
950-1050m	Flowering	New flush				Fruiting			Wintering	New flush	Flowering	New flush

Figure 5.2 A brief demonstration of rubber trees major phonological stages at different elevation. Information was revised and adapted from Meti et al. (2014) for rubber plantations located at elevations lower than 432m, while data for elevation higher than this range was collected from Jia (2006). The red box denoted the tapping period for lower elevation regions, while the blue box represents the tapping season in marginal expansion areas (Jiang 1988). The highlighted grey filled box stands for disease (*Oidium heveae* Steinm and *Phytopthora palmivora* Butl.) caused leaf fall.

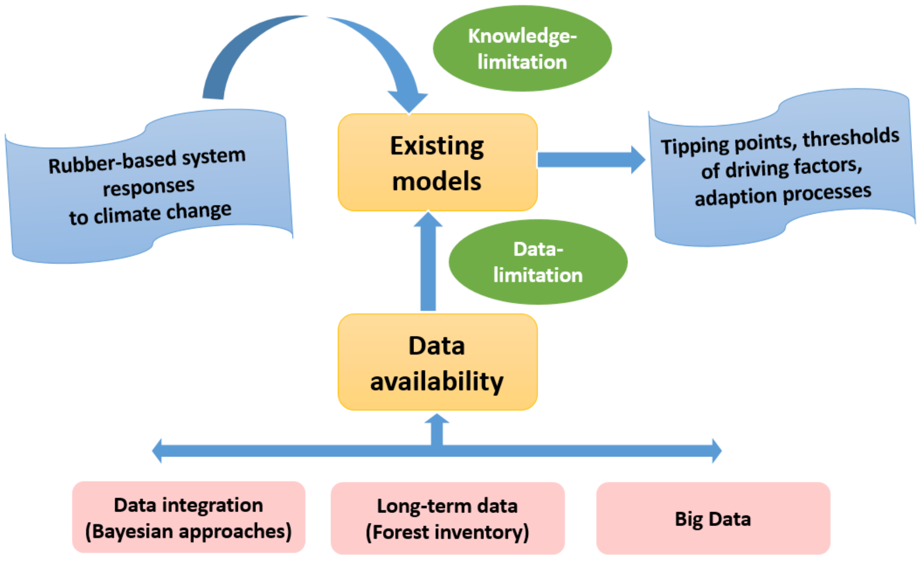

Figure 5.3 Integration of existing models and available data for rubber-based system response simulation, under the context of climate change. Adapted and revised from Zavala et al., 2017.

provide reference for decision making (Medlyn et al., 2011; Figure 5.3). We suggest that a general research priority should be to improve model predictions through a strategic, model-based approach to research. Ideally, models and experimental research should be closely integrated. A modeling framework can be used to generate research questions and identify key sets of measurements needed. Experimental data needs to be used critically to test model performance. In forests in particular, long-term, intensively studied experiments are needed to generate sufficient data to test alternative model hypotheses. Moreover, concerning the same research topic, a model comparison should be carried out to select better performaning models. Following the experiences discussed before, a set of recommendations and remarks are listed below for future studies in this field of research:

1) To make use of stakeholders' knowledge for a priori investigations; thereafter, based on data availability choose model types;
2) The selection of appropriate spatial-temporal scales used for modelling are a crucial part of research planing;
3) The uncertainties revealed by the research should be comunicated for decision making groups, and if possible, become an integral part of research;
4) It is always necessary transferring scientific outputs into tangible expressions for other non-scientific groups. The feedback should be integrated into action plans;

5) For better adaption and mitigation of climate change impacts, a climate smart landscape approach is advised;
6) The used modelling tools could be adopted in other rubber-cultivated regions, with regional customization for better performance;
7) Data sharing, transforming and exchange processes among various rubber growth countries will contribute to global sustainable rubber cultivation.

References

Ahrends, A., Hollingsworth, P. M., Ziegler, A. D., Fox, J. M., Chen, H. F., Su, Y. F., Xu, J. C., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Global Environmental Change. 34, 48-58.

Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytologist. 165, 351-372.

Akaike H. 1981. Likelihood of a model and information criteria. J. Econom. 16, 3-14

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO irrigation and drainage paper 56. FAO, Rome.

Almeida, A.C., Sands, P.J., Bruce, J., Siggins, A.W., Leriche, A., Battaglia, M., Batista. T.R., 2009. Use of a spatial process-based model to quantify forest plantation productivity and water use efficiency under climate change scenarios. In R.S. Anderssen, R.D. Braddock, and L.T.H. Newham (eds.) Interfacing Modelling and Simulation with Mathematical and Computational Sciences. MODSIM Congress. Cairns, Australia. 13–17 July 2009.

Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonesca, S., Loos, R., 2010. Mapping the effect of spatial and temporal variation in climate and soils in Eucalyptus plantation production with 3-PG, and process-based growth model. Forest Ecology and Management 259, 1730-1740.

Angelsen, A., Brockhaus, M., Kanninen, M., Sills, E., Sunderlin, W.D., Wertz-Kanounnikoff, S., 2009. Realising REDD+: National strategy and policy options. In report of Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Annamalainathan, K., Jacob, J., Vinod, K.K., Thomas, K.U., Sreelatha, S., Sumesh, K.V., Suryakumar, M., 2013. Tapping induced biomass loss in nature rubber (*Hevea brasiliensis*) trees: Putative factors explaining the unknown mechanism. Rubber Science. 26 (1): 23-35

Apel, U. 1996. Der dorfwald von moxie, traditionelle dorfwaldbewirtschaftung in Xishuangbanna, Südwest-China, Göttingen.

Ariff, E.A.R.E., Suratman, M.N., Abdullah. S., 2017. Modelling of carbon sequestration in rubber (*Hevea brasiliensis)* plantations. In"Managing forest ecosystems: the challenge of climate change". Bravo., F., Jandl, R., LeMay, V., (eds). Volume 34 of the series Managing Forest Ecosystems. 385-402. Springer International Publishing Switzerland 2017.

Arifin, J. Estimasi Penyimpanan C Pada Berbagai Sistem Penggunaan Lahan di Kecamatan Ngantang, Malang, Jurusan Tanah, Fakultas Pertanian, Universitas Brawijaya, Malang, 2001,61pp.

ASB (Alternatives to Slash-and-Burn Programme). 1999. Carbon sequestration and trace gas emissions in slash-and-burn and alternative land uses in the humid tropics. Climate Change Working Group Final Report. Phase II. Nairobi.

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P. S. A., Dubayah, R., Friedl, M. A., Samanta, S., Houghton, R. A., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change 2, 182-185.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Lloyd, J., Monteagudo, A., Neill, D.A., Patiño, S., Pitman, N.C.A., Silva, N., Martínez, R.V., 2004. Variation in wood density determines spatial patterns in Amazonian forest biomass. Global Change Biology 10, 545–562.

Bao, Y. J., Li, Z. H., Ma, Y. H., Dong, Y. Y., Song, G. B., Wang, H. M., 2008. Effects of rubber plantation on tropic rainforest ecosystem in Nabanhe river basin. Ecology and Environment 17, 734-739. (in Chinese)

Bartell, *S.M.,* Gardner, R.H.*,* O'Neill*,* R.V.*, 1992.* Ecological Risk Estimation Lewis Publishers, Chelsea, MI. pp. 252

Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forest Research 2, 49-53

Beckschäfer, P., 2017. Obtaining rubber plantation age information from very dense Landsat TM & ETM + time series data and pixel-based image compositing. Remote Sensing of Environment 196, 89-100.

Blagodatsky, S., Xu, J.C., Cadisch, G., 2016. Carbon balance of rubber (*Heavea brasiliensis*) plantations: a review of uncertainties at plot, landscape and production level. Agriculture, Ecosystems & Environment221, 8-19.

Blennow, K., Persson, J., Tomé, M., Hanewinkel, M., *2012.* Climate change: believing and seeing implies adapting. PLoS ONE *7,* e50182

Blozan, W., 2006. Tree measuring guidelines of the Eastern Native Society. Bulletin of the (Eastern Native Tree Society) ENTS. 1, 3-10.

Breiman, L., Friedman, J.H., Olshen, R.A., and Stone, C.I. 1984. Classification and regression trees. Belmont, Calif.: Wadsworth

Brigham, A.P. and McFarlane, C.T., 1916. Essentials of Geography. New York, NY: American Book Company, PP. 407

Brockerhoff, E.G., Jactel, H., Parrotta, J., Ferraz, S.F.B., 2013. Role of eucalypt and other planted forests in biodiversity conservation and the provision of biodiversity-related ecosystem services. Forest Ecology and Management 301, 43-50.

Brown, S. 2002. Measuring carbon in forests: current status and future challenges. Environmental Pollution 116, 363-372

Brown, S., Billespie, A.J.R., Lugo, A.E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35, 881-902.

Boogaard, H.L., De Wit, A.J.W., te Roller, J.A., Van Diepen, C.A., 2014. WOFOST Control Centre 2.1; User's Guide for the WOFOST Control Centre 2.1 and the Crop Growth Simulation Model WOFOST 7.1.7. Wageningen University & Research Centre, Wageningen (Netherlands), Alterra

Boote, K.J., Jones, J.W., White, J.W., Asseng, S., Lizaso, J.I., 2013. Putting

mechanisms into crop production models. Plant, Cell & Environment 36, 1658-1672
Borchert, R., 1994. Water status and development of tropical trees during seasonal drought. Trees 8, 115-125.
Borchert, R., Calle, Z., Strahler, A.H., Baertschi, A., Magill, R.E., Broadhead, J.S., Kamau, J., Njoroge, J., Muthuri, C., 2015. Insolation and photoperiodic control of tree development near the equator. New Phytologist 205, 7-13.
Bouriaud, O., Soudani, K., Bréda, N., 2003. Leaf area index from litter collection: impact of specific leaf area variability within a beech stand. Canadian Journal of Remote Sensing 29, 371-380.
Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analyses of soils.Agronomy Journal 54, 464-465.
Cahyo, A.N., Babel, M.S., Datta, A., Prasad, K.C., Clemente, R.S., 2016. Evaluation of land and water management options to enhance productivity of rubber plantation using WaNuLCAS model. Agrivita 38, 93-103
Cao, M. and Zhang, J. 1997. Tree species diversity of tropical forest vegetation in Xishuangbanna, SW China. Biodiversity and Conservation 6, 995-1006
Chan, H., 2000. Milestones in Rubber Research. Malaysian Rubber Board, pp. 2–15
Chantuma, A., Wichitchonlachai, T., Chantuma, P., 2012. Rubber new planting in Thailand: towards the world affected on climate change. Rubber Thai Journal 1, 40–47.
Chantuma, p., Lacointe, A., Kasemsap, P., Thanisawanyangkura, S., Gohet, E., Clément, A., Guilliot, A., Améglio, T., Thaler, P. 2009. Carbohydrate storage in wood and bark of rubber trees submitted to different level of C demand induced by latex tapping. Tree Physiology 29, 1021-1031
Chapman, E., 1991. The expansion of rubber in southern Yunnan, China. The Geographical Journal 157,36–44.
Chaudhuri, D., Vinod, K.K., Potty, S.N., Sethuraj, M.R., Pothen, J., Reddy, Y.A.N., 1995. Estimation of biomass in Hevea clones by regression method: Relation between girth and biomass. Indian Journal of Natural Rubber Research 8, 113-116.
Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forest. Oecologia 145, 87-99.
Chave, J., Muller-Landau, H.C., Baker, T.R., Easdale, T.A., Steege, H.T., Webb, C.O., 2006. Regional and phylogenetic variation of wood density across 2,456 Neo-tropical tree species. Ecological Applications 16, 56–2367.
Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2015. Improved allometric models to estimate the aboveground biomass of tropical trees. Global

Change Biology 20, 3177-3190.

Chen, B. Q., Cao, J. H., Wang, J. K., Wu, Z. X., Tao, Z. L., Chen, J. M., Yang, C., Xie, G. S., 2012. Estimation of rubber stand age in typhoon and chilling injury afflicted area with Landsat TM data: A case study in Hainan Island, China. Forest Ecology and Management 274, 222-230.

Chen, B. Q., Wu, Z. X., Wang, J. K., Dong, J. W., Guan, L. M., Chen, J. M., Yang, K., Xie, G. S., 2015. Spatio-temporal prediction of leaf area index of rubber plantation using HJ-1A/1B CCD images and recurrent neural network. ISPRS Journal of Photogrammetry and Remote Sensing102, 148-160.

Chen, G.H., Huang, H.S., An, Z.W., 2008. Preliminary report on physiological characteristic of young rubber clones by cold acclimation. Tropical Agricultural Science & Technology 31, 1-3.

Cheng, C. M., Wang, R. S., Jiang, J. S., 2007. Variation of soil fertility and carbon sequestration by planting *Heveabrasiliensis* in Hainan Island, China. Journal of Environmental Sciences 19, 348-352.

Chen, H.F., Yi, Z.F., Schmidt-Vogt, D., Ahrends, A., Beckschäfer, P., Kleinn, C., Ranjitkar, S., Xu, J.C., 2016. Pushing the limits: the pattern and dynamics of rubber monoculture expansion in Xishuangbanna, SW China. PLOS ONE 11, e0150062.

Chukwuemeka, O., 2016. Wood Density of Rubber (*Hevea Brasiliensis*) Grown in South-Eastern Nigeria for Utilization Purposes.International Journal of Advanced Research in Social Engineering and Development Strategies 4, 40-45

Cienciala, E., and Tatarinov, F.A. 2006. Application of BIOME-BGC model to managed forests 2. Comparison with long-term observations of stand production for major tree species. Forest Ecology and Management 237, 252-266

Clarke, L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, R. Richels, 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, 7 DC., USA, pp.154

Clermont-Dauphin, C., Suvannang, N., Hammecker, C., Cheylan, V., Pongwichian, P., Do, F.C., 2013. Unexpected absence of control of rubber tree growth by soil water shortage in dry subhumid climate. Agronomy for Sustainable Development 33, 531-538.

Clough, Y., Krishna, V.V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A.D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., Holtkamp, A.M., Horandl, E., Irawan, B., Surati Jaya, ¨ I.N., Jochum, M., Klarner, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Kurniawan, S., Leuschner, C., Maraun, M., Melati, D.N., Opfermann, N. Perez-Cruzado, C., Edho Prabowo, W., Rembold, K., Rizali, ´ A., Rubiana, R., Schneider, D., Tjitrosoedirdjo, S.S., Tjoa, A., Tscharntke, T., Scheu, S., 2016. Land-use choices follow profitability at the expense of ecological functions in

Indonesian smallholder landscapes. Nature Communiations 7, 13137.
Corpuz, O.S., Abas, E.L., Salibio, F.C., 2014. Potential carbon storage of rubber plantations. Indian Journal of Pharmaceutical and Biological Research (IJPBR) 2, 73-82.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.
Cotter, M., Asch, F., Hilger, T., Rajaona, A., Schappert, A., Stuerz, S., Yang, X.Q., 2017. Measuring leaf area index in rubber plantations- a challenge. Ecological Indicators 82, 357-366.
Cotter, M., Berkhoff, K., Gibreel, T., Ghorbani, A., Golbon, R., Nuppenau, E., Sauerborn, J., 2014. Designing a sustainable land use scenario based on a combination of ecological assessments and economic optimization. Ecological Indicators 36, 779-787.
Cotter, M., Häuser, I., Harich, F.K., He, P., Sauerborn, J., Treydte, A.C., Martin, K., Cadisch, G., 2017. Biodiversity and ecosystem services−A case study for the assessment of multiple species and functional diversity levels in a cultural landscape. Ecological Indicators 75, 111-117.
Cowie, A. L., Kirschbaum, M. U. F., Ward, M., 2007. Options for including all lands in a future greenhouse gas accounting framework: Environmental Science & Policy 10, 306-321.
Dang, C.L., Wu, Z.L.and Zhang, Q. 1997. A study on biomass of the ravine tropical rain forest in Xishuangbanan. Acta Botanica Yunnanica Suppl.IX, 123-128 (in Chinese)
de Blécourt, M., Brumme, R., Xu, J.C., D.Corre, M., Veldkamp, E., 2013. Soil carbon stocks decrease following conversion of secondary forests to rubber (*Hevea brasiliensis*) plantations. PLoS ONE 8, e69357.
De'ath, G. and Fabricius, K.E., 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. Ecology 81, 3178-3192.
DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., C., d. S. J., 2007.Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science & Policy 10, 385-394.
Dey, S. K., Chaudhuri, D., Vinod, K. K., Pothen, J., Sethuraj, M. R., 1996. Estimation of biomass in Hevea clones by regression method: 2. Relation of girth and biomass for mature trees of clone RRIM 600. Indian Journal of Natural Rubber Research 9, 40-43.
Dijkman, M.J., 1951. *Hevea* – Thirty years of research in the Far East. University of Miami Press U.S.A., Coral Gables, Florida, pp. 329.
Ditzer, T., R. Glauner, M. Förster, P. Köhler and A. Huth. 2000. The process-based stand growth model FORMIX 3-Q applied in a GIS environment for growth and yield analysis in a tropical rain forest. Tree Physiology 20, 367–381
Dong, J. W., Xiao, X. M., Chen, B. Q., Torbick, N., Jin, C., Zhang, G. L., Biradar, C.,

2013. Mapping deciduous rubber plantations through integration of PALSAR and multi-temporal Landsat imagery. Remote Sensing of Environment 134, 392-402.

Dong, J. W., Xiao, X. M., Sheldon, S., Biradar, C., Xie, G. S., 2012. Mapping tropical forests and rubber plantations in complex landscapes by integrating PALSAR and MODIS imagery.ISPRS Journal of Photogrammetry and Remote Sensing 74, 20-33.

Dong, Y.X., Zhang, Y.p., Sha, L.Q., Ji, H.L., Zhou, W.J., Liu, Y.T., Zhang, X., Lin, Y.x., 2015. Impacts of fertilizer application on CO2 emissions in rubber (Hevea brasilensis) plantation in Xishuangbanna, Southwest China. Chinese Journal of Ecology 34, 2576-2582.

Duff, G.A., Myers, B.A., Williams, R.J., Eamus, D., O'Grady, D., Fordyce, I.R., 1997. Seasonal patterns in soil moisture, vapour pressure deficit, tree canopy cover and predawn water potential in a northern Australian savanna. Australian Journal of Botany 45, 211–224

Eamus, D., Prior, L. 2001. Ecophysiology of trees of seasonally dry tropics: comparisons among phenologies. Advances in Ecological Research. 32, 113–197

Eastaugh C.S., Pötzelsberger E., Hasenauer H. Assessing the impacts of climate change and nitrogen deposition on Norway spruce (Picea abies L. Karst) growth in Austria with BIOME-BGC. Tree Physiology. 2011.31,262–274.

Egbe, A.E., Tabot, P.T., Fonge, B.A., Bechem, E., 2012. Simulation of the impacts of three management regimes on carbon sinks in rubber and oil palm plantation ecosystems of South- Western Cameroon. Journal of Ecology and The Natural Environment 4, 154-162.

Ekadinata, A., Widayati, A., Vincent, G., 2004. Rubber agroforest identification using object-based classification in Bungo District, Jambi, Indonesia. In: 25th ACRS, Chiang Mai, Thailand.

Engel, S., Palmer, C., 2008. Payments for environmental services as an alternative to logging under weak property rights: the case of Indonesia. Ecological Economics 65, 799–809

Ensslin, A., Rutten,G., Pommer, U., Zimmermann, R., Hemp, A., Fischer, M., 2015. Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. Ecosphere 6, 1-15.

Environmental Systems Research Institute (ESRI). 2012. ArcGIS Release 10.1. Redlands, CA.

FAO, 2001. Non-forest tree plantations. Report based on the work of W. Killmann. Forest plantation thematic papers, working paper 6. Forest Resources Development Service, Forest Resources Division. FAO, Rome (unpublished).

FAO, 2009. ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e/md012e00.pdf. Accessed 4. Jan 2015.

FAO, 2013. Food and Agriculture Organization of the United Nations. Processing of Natural Rubber. Accessed 7 Jun. 2016 through web link: http://ecoport.org/ep?SearchType=earticleView&earticleId=644&page=4343.

FAO. 2013. Financing climate-smart agriculture, Climate-Smart Agriculture Sourcebook module 14, Rome. pp. 375–406.

FAO/UNESCO., 1998. World Reference Base for Soil Resources. Rome.

Fearnside, P.M., 1995. Potential impacts of climatic change on natural forests and forestry in Brazilian Amazonia. Forest Ecology and Management 78, 51-70.

Fearnside, P.M. 2000. Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climate Change 46, 115-158.

Fearnside, P.M., Laurance, W.F., 2003. Comment on 'Determination of deforestation rates of the world's humid tropical forest'. Science 299, 1015.

Fearnside, P.M., Laurance, W.F. 2004. Tropical deforestation and greenhouse gas emissions. Ecological Applications 14, 982-986.

Feng, Z.L., Zheng, Z., Zhang, J.H., Cao, M., Sha, L.Q., Deng, J.W. 1998. Biomass and its allocation of a tropical wet seasonal rainforest in Xishuangbanna. Acta Ecologica Sinica 22, 481-488. (in Chinese).

Flewelling, J.W., and Pienaar, L.V., 1981. Multiplicative regression with lognormal errors. Forest Science 27, 281–289.

Fontes, L., Bontemps, J.D., Bugmann, H., van Oijen, M., Gracia, C., Kramer, K., Lindner, M., Rötzer, T., Skovsgaard, J.P., 2010. Models for supporting forest management in a changing environment. Forest Systems 19, 8-29

Fox, J., 2000. How blaming 'slash and burn' farmers is deforesting mainland Southeast Asia. In, Asia Pacific Issues; No. 47, Honolulu: East-West Center.

Fox, J. and Castella, J.-C., 2013. Expansion of rubber (*Hevea brasiliensis*) in mainland Southeast Asia: what are the prospects for smallholders? The Journal of Peasant Studies. 40, 155-170

Fox, J., Castella, J.-C., Ziegler, A. D., 2014. Swidden, rubber and carbon: Can REDD+ work for people and the environment in montane mainland Southeast Asia? Global Environmental Change 29, 318-326.

Fox, J., Vogler, J., 2005. Land-use and land-cover change in Montane Mainland Southeast Asia. Environmental Management 36, 394-403.

Fu, Y., Chen, J., Guo, H., Hu, H., Chen, A., Cui, J., 2010. Agrobiodiversity loss and livelihood vulnerability as a consequence of converting from subsistence farming systems to commercial plantation- dominated systems in Xishuangbanna, Yunnan, China: a household level analysis. Land Degradation & Development 21, 274-284.

Fujino, J., R. Nair, M. Kainuma, T. Masui, Y. Matsuoka, 2006. Multi-gas mitigation analysis on stabilization scenarios using AIM global model. The Energy Journal Special Issue on Multi-Greenhouse Gas Mitigation and Climate Policy 27, 343-353

Gao, F., Zhang, Y.P., Liu, W.J., Tang, J.W., Deng, X.B., 2009. Characteristics of base flow in tropical seasonal rainforest catchments in Xishuangbanna of Yunnan province, southwest China. Chinese Journal of Ecology 28, 1949-1955.

Garten Jr., C.T. and Hanson, P.J., 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. Geoderma 136, 342-352.

Garten Jr., C.T. and Van Miegroet, H. 1994. Relationship between soil N dynamics and natural 15N abundance in plant foliage from Great Smoty Mountain National Park. Canadian Journal of Forest Research 24, 1636-1645.

Gibbs, H. K., Brown, S., Niles, J. O., Foley, J. A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2, 1-13.

Gibreel, T.M., Herrmann, S., Berkhoff, K., Nuppenau, E., Rinn, A., 2014. Farm types as an interface between an agroeconomical model and CLUE-Naban land change model: Application for scenario modelling. Ecological Indicators 36, 766-778.

Golbon, R., Ogutu, J.O., Cotter, M., Sauerborn, J., 2015. Rubber yield prediction by meterological conditions using mixed models and multi-model inference techniques. International Journal of Biometeorology 59, 1747-1759.

Gouyon, A., de Foresta, H., Levang, P., 1993. Does "Jungle Rubber" Deserve its Name? An analysis of Rubber Agroforestry Systems in Southeast Sumatra. Agroforestry Systems 22, 181-206.

GPG LULUCF IPCC, 2004. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Intergovernmental Panel on Climate Change. Online: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/.

Grace, J., 2004. Understanding and managing the global carbon cycle. Journal of Ecology 92, 189-202.

Grace, J., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H.S., Nobre, C., Moncrieff, J., Massheder, J., Malhi, Y., Wright, I., Gash, J., 1995. Carbon Dioxide Uptake by an Undisturbed Tropical Rain Forest in Southwest Amazonia, 1992 to 1993. Science 270, 778-780.

Green, D.G. and Sadedin, S., 2005. Interactions matter-complexity in landscapes and ecosystems. Ecological Complexity. 2, 117-130

Grist, P., Menz, K., and Thomas. 1998. Modified BEAM Rubber Agroforestry Models: RRYIELD and RRECON. AClAR Technical Reports Series No. 42, pp. 43.

Gunathilaka, R.P.D., Smart, J.C.R. & Fleming, C.M. 2017. Climatic Change 140, 577.

Guo, Y.Q., Yang, Y.M., Tang, J.S., Chen, S.W., Lei, F.G., Wang, J.H., Yang, Z.H., Yang, G.Z., 1987. The vegetation in the natural reserves of Xishuangbanna. In: Xu, Y.C., Jiang, H.Q., Quan, F. (Eds.), Proceedings of Synthetical Investigation of Xishuangbanna Nature Research. Yunnan Science and Technology Press, Kunming, China, pp. 88-169.

Gustafson, E. J., A. M. G. De Bruijn, B. R. Miranda, B. R. Sturtevant, and M. E. Kubiske. 2017. Do rising temperatures always increase forest productivity? Interacting effects of temperature, precipitation, cloudiness and soil texture on tree species growth and competition. Environmental Modelling and Software. 97, 171-183

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu, S., van Noordwijk, M., 2011. Measuring carbon stocks across land use systems: a manual. pp. 154. World Agroforestry Centre (ICRAF), SEA regional office, Bogor, Indonesia.

Häring, D and Körner, C., 2004. CO_2 enrichment reduces the relative contribution of latex and latex-related hydrocarbons to biomass in *Euphorbia lathyris*. Plant, Cell & Environment 27, 209-217.

Harmon, M.E., Fasth, B., Halpern, C.B., Lutz, J.A. 2015. Uncertainty analysis: an evaluation metric for synthesis science. Ecosphere 6, 63. http://dx.doi.org/10.1890/ES14-00235.1

Harmon, M. E., Phillips, D. L., Battles, J. J., Rassweiler, A., Hall Jr., R. O., Lauenroth, W. K., 2007. Quantifying uncertainty in net primary production measurements. Editors: Fahey, T. J. and Knapp, A. K. Principles and standards for measuring net primary production in long-term ecological studies. Oxford University Press, Oxford, UK. pp. 238–260.

Hasenauer, H., Petritsch, R., Zhao, M., Boisvenue, C., Running, S.W., 2012. Reconciling satellite with ground data to estimate forest productivity at national scales. Forest Ecology and Manage 276, 196-208

Hashimotio, T., Kojima, K., Tang, T. Sasaki, S., 2000. Changes in carbon storage in fallow forests in the tropical lowland of Berneo. Forest Ecology and Management 126, 331-337.

Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R., Bernoux, M., Saint-André, L., 2011. Estimating tree biomass of Sub-Saharan African forests: a review of available allometric equations. Silva Fennica 45, 477-569.

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, M., Kainuma, M. 2008. Global GHG emissions scenarios under GHG concentration stabilization targets. Journal of Global Environment Engineering 13, 97-108.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surface for global land areas. International Journal of Climatology 25, 1965–2198.

Hlásny, T., Barcza, Z., Fabrika, M., Balázs, B., Churkina, G., Pajtík, J., Sedmák, R., Turčáni, M., 2011. Climate change impacts on growth and carbon balance of forests in Central Europe. Climate Research 47, 219-236.

Houghton, R.A. 2005. Tropical deforestation as a source of greenhouse gas emissions. Tropical Deforestation and Climate Change. Ed Mutinho and Schwartzman (Belem: IPAM).

Houghton, R.A., 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945-958.

Houghton, R.A. 2012. Carbon Emissions and the Drivers of Deforestation and Forest Degradation in the Tropics. Current Opinion in Environmental Sustainability 4, 597-603.

Houghton, R.A., Goodale, C.L., 2004. Effects of land-use change on the carbon balance of terrestrial ecosytems. In: DeFries, R.S., asner, G.P., Houghton, R.A. (Eds.), Ecosystems and Land Use Change. American Geophysical Union, Washington, DC, pp. 85-98.

Hu, H.B., Liu, W.J., Cao, M., 2008. Impact of land use and land cover changes on ecosystem services in Menglun, Xishuangbanna, Southwest China. Environmental Monitoring and Assessment 146, 147-156.

Huang, Q., Li, Y.D., Lai, J.Z., Peng, G.J., 1991. Study on biomass of tropical mountain rain forest in Limushan, Hainan Island. Acta Phytoecologica et

Geobotanica Sinica 15, 197-206. (in Chinese)

Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Monika Strömgren, Marcel van Oijen, Wallin, G., 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytologist 173, 463-480.

IGBP Terrestrial Carbon Working Group. 1998. The terrestrial carbon cycle: implications for the Kyoto Protocol. Science 280, 1393-1394.

IPCC.1997. "Revised 1996 IPCC guidelines for national greenhouse gas inventories". Available online: http://www.ipcc-nggip.iges.or.jp/public/gl/invs5d.html.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Jantz, P., Goetz, S., Laporte, N., 2014. Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics. Nature Climate Change 4, 138-142.

Jayasooryan, K.K., Satheesh, R., Krishnakumar, R., Jacob, J., 2015. Occurrence of extreme temperature events - A probable risk on natural rubber cultivation. Journal of Plantation Crops 43, 218-224.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Forest Science49, 12-35.

Jia, K.X., 2006. Study on growth change of rubber plantation along an altitudinal gradient in Xishuangbanna, Southwest China (Master's thesis). http://ir.xtbg.org.cn/handle/353005/391 (accessed 6 Jun 2014).

Jia, K.X., Zheng, Z. Zhang, Y.P., 2006. Changes of rubber plantation aboveground biomass along elevation gradient in Xishuangbanna. Chinese Journal of Ecology 25, 1028-1032. (in Chinese).

Jiang, A.L., 1988. Climate and natural production of rubber (*Hevea brasiliensis*) in Xishuangbanna, southern part of Yunnan province, China. International Journal of Biometeorology 32, 280-282.

Johnston, A. 1989. "Diseases and Pests," Rubber, New York: Longman Scientific and Technical. pp. 413-458.

Jones, D.L., Cross, P., Withers, P.J.A., DeLuca, T.H., Robinson, D.A., Quilliam, R.S., Harris, I.M., Chadwick, D.R., Edwards-Jones, G., 2013. Nutrient-stripping: the global disparity between food security and soil nutrient stocks. Journal of Applied Ecology 50, 851-862.

Jusoff, K., Yusoff, M.H.M., 2009. New approaches in estimating rubberwood standing volume using airborne hyperspectral sensing. Modern Applied Science 3, 62-70.

Kangas, A., 2010. Value of forest information. European Journal of Forest Research 129, 863–874.

Karssenberg, D., Schmitz, O., Salamon, P., de Jong, K., and Bierkens, M. F. P. 2010.

A software framework for construction of process-based stochastic spatio-temporal models and data assimilation. Environmental Modelling & Software 25, 489-502.

Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Annals of Forest Science 72, 145-167.

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment. Forest Ecology and Management 352, 9-20.

Ketterings, Q. M., Coe, R., Van Noordwijk, M., Ambagau, Y., Palm, C. A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management 146, 199-209.

Khun, K., Mizoue, N., Yoshida, S., Murakami, T., 2008. Stem volume equation and tree growth for rubber trees in Cambodia. Journal of Forest Planning 13, 335-341.

Killmann, W. and Hong, L.T., 2000. Rubberwood-the success of an agriculture by-products. Unasylva 51, 66-72

Kirschbaum, M. U. F., 2006. Temporary carbon sequestration cannot prevent climate change. Mitigation and Adaptation Strategies for Global Change 11, 1151-1164.

Knapic, S., Louzada, J.L., Leal, S., Pereira, H., 2008. Within-tree and between-tree variation of wood density components in cork oak trees in two sites in Portugal. Forestry 81, 465-473.

Koh, L.P., Wilcove, D.S., 2008. Oil palm: disinformation enables deforestation. Trends in Ecology & Evolution 24, 67-68.

Kohler, T., Wehrli, A., Jurek, M. 2014. Mountains and climate change: A global concern. Sustainable Mountain Development Series. Bern, Switzerland, Centre for Development and Environment (CDE), Swiss Agency for Development and Cooperation (SDC) and Geographica Bernensia. pp. 136.

Korzukhin, M.D., M.T. Ter-Mikaelian and R.G. Wagner. 1996. Process versus empirical models: which approach for forest ecosystem management? Canadian Journal of Forest Research 26, 879-887.

Kositsup, B., Montpied, P., Kasemsap, P., Thaler, P., Ame´glio, T., Dreyer, E., 2009. Photosynthetic capacity and temperature responses of photosynthesis of rubber trees (*Hevea brasiliensis* Müll. Arg.) acclimate to changes in ambient temperatures. Trees 23, 357-365.

Kotowska, M.M., Leuschner, C., Triadiati, T., Meriem, S., Hertel, D., 2015. Quantifying above-and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). Global Change Biology 21, 3620–3634.

Kropff, M.J., and van Laar, H.H., 1993. Modelling Crop–Weed Interactions. CAB International, Wallingford, UK, pp. 274

Krukanont, P., Prasertsan, S., 2004. Geographical distribution of biomass and potential sites of rubber wood fired power plants in Southern Thailand. Biomass Bioenergy 26, 47-59.

Kumagai, T., Mudd, R.G., Miyazawa, Y., Liu, W., Giambelluca, T.W., Kobayashi, N., Lim, T.K., Jomura, M., Matsumoto, K., Huang, M.Y., Chen, Q., Ziegler, A., Yin, S., 2013. Simulation of canopy CO_2/H_2O fluxes for a rubber (*Hevea brasiliensis*) plantation in central Cambodia: The effect of the regular spacing of planted trees. Ecological Modelling 265, 124-135.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H., 2012. Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agriculture, Ecosystems & Environment 158, 216-224.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H., 2012. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. Agriculture, Ecosystems & Environment 158, 225-234.

Laclau, J.-P., Silva, E.A.D., Lambais, G.R., Bernoux, M., Maire, G.L., Stape, J.L., Bouillet, J.-P., Goncalves, J.L.D.M., Jourdan, C., Nouvellon., Y., 2013. Dynamics of soil exploration by fine roots down to a depth of 10 m throughout the entire rotation in Eucalyptus grandis plantations. Frontiers in Plant Science 4, 243. doi: 10.3389/fpls.2013.00243

Lacointe, A., 2000. Carbon allocation among tree organs: a review of basic processes and representation in functional-structural tree models. Annals of Forest Science 57, 521–533.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95, 209-228.

Langenberger, G., Cadisch, G., Martin, K., Min, S., Waibel, H., 2017. Rubber intercropping: a viable concept for the 21st century? Agroforestry Systems 91,577-596.

Langenberger, G., Ghorbani, A., Liu, J., 2008. Rubber-boom in Xishuangbanna-where will it end? In: The Uplands Program. International Symposium. Interdependencies between upland and lowland agriculture and resource management. 1-4 April 2008, Stuttgart, Germany. pp. 185-186

Lagergren, F., Grelle, A., Lankreijer, H., Mölder, M., Lindroth, A., 2006. Current carbon balance of the forested area in Sweden and its sensitivity to global change as simulated by Biome-BGC. Ecosystems 9, 894-908

Laub, M., Blagodatsky, S., Lang, R., Yang, X.Q., Cadisch, G., 2018. A mixed model for landscape soil organic carbon prediction across continuous profile depth in the mountainous subtropics. Geoderma 330, 177-192.

Lauenroth, W.K., Wade, A.A., Williamson, M.A., Ross, B.E., Kumar, S., Cariveau, D.P., 2006. Uncertainty in calculations of net primary production for grasslands. Ecosystems, 9, 843-851.

Lemos Filho, J.P., Nova, N.A.V., Pinto, H.S., 1993. Base temperature and heat units for leaf flushing emission and growth of *Hevea brasiliensis* Müell. Arg. International Journal of Biometeorology 37, 65-67.

Lemos Filho, J.P., Nova, N.A.V., Pinto, H.S., 1997. A model including photoperiod in degree days for estimating *Hevea* bud growth. International Journal of Biometeorology 41, 1-4.

Lenz, A., Vitasse, Y., Hoch, G., Körner, C., 2014. Growth and carbon relations of temperate deciduous tree species at their upper elevation range limit. Journal of Ecology 102, 1537-1548.

Li, H.M., Aide, T.M., Ma, Y.X., Liu, W.J., Cao, M., 2007. Demand for rubber is causing the loss of high diversity rain forest in SW China. Biodiversity and Conservation 16, 1731-1745.

Li, H.M., Ma, Y.X., Aide T.M., Liu, W.J., 2008. Past, present and future land-use in Xishuangbanna, China and implications for carbon dynamics. Forest Ecology and Management 255, 16-24.

Li, M. and Yuan, F. 2008. Rubber plantations – Green desert. Chinese National Geography 4, 60-78.

Li, Y.D., Wu, Z.M., Zeng, Q.B., Zhou, G.Y., Chen, B.F., Fang, J.Y., 1996. Carbon pool and carbon dioxide dynamics of tropical mountain rainforest ecosystem at Jianfengling, Hainan Island. Acta Ecologica Sinica 18. 371-378. (in Chinese)

Li, Z., Fox, J.M., 2012. Mapping rubber tree growth in mainland Southeast Asia using time-series MODIS 250m NDVI and statistical data. Applied Geography 32, 420-432.

Lippe, M., Marohn, C., Hilger, T., Dung, N.V., Vien, T.D., Cadisch, G., 2014. Evaluating a spatially-explicit and stream power-driven erosion and sediment deposition model in Northern Vietnam. Catena 120, 134-148

Liu, H. M., Gao, L., Zheng, Z., Feng, Z. L., 2006. The impact of *Amomum villosum* cultivation on seasonal rainforest in Xishuangbanna, Southwest China. Biodiversity and Conservation 15, 2971-2985.

Liu, H.X., Blagodatsky, S., Giese, M., Liu, F., Xu, J.C., Cadisch, G., 2016. Impacts of herbicide application on soil erosion and induced carbon loss in a rubber plantation of Southwest China. Catena 145, 180-192.

Liu, M., Liu, G.H., Gong, L., Wang, D.B., Sun, J., 2014. Relationships of biomass with environmental factors in the grassland area of Hulunbuir, China. PloS One 9, 1-8.

Liu, S. L., Deng, L., Dong, S. K., Zhao, Q. H., Yang, J. J., Wang, C., 2014, Landscape connectivity dynamics based on network analysis in the Xishuangbanna Nature Reserve, China. Acta Oecologica 55. 66-77.

Liu, S.J., Zhou, G.S., Fang, S.B., 2015. Spatial-temporal characteristics of rubber chilling injury in China during 1961-2010. Chinese Journal of Ecology 34, 1282-1288.

Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters 2, 004000

Lobell, D.B., Schlenker, W.S., Costa-Roberts, J. 2011. Climate trends and global crop production since 1980. Science 333, 616-620

Lu, X.T., Tang, J.W., Yu, G.R., Zhang, Y.P. 2006. Carbon storage and distribution of tropical seasonal rain forest in Xishuangbanna, Yunnan. Journal of Mountain Science 24, 277-283. (in Chinese).

Lugo, A.E. and Brown, S., 1992. Tropical forests as sinks of atmospheric carbon. Forest Ecology and Management 54, 239-255.

Luo, P., He, J.J., Yao, Y.L., Dai, X.H., Cheng, R.X., Wang, L.F., 2012. Differential responses of two rubber tree clones to chilling stress. African Journal of Biotechnology 11, 13466-13471.

Lusiana, B., 2013. Salience, credibility and legitimacy in land use change modeling: model validation as product or process? PhD thesis. University of Hohenheim. pp. 78

Lusiana, B., Van Noordwijk, M., Cadisch, G., 2012.Land sparing or sharing? Exploring livestock fodder options in combination with land use zoing and consequences for livelihoods and net carbon stocks using the FALLOW model. Agriculture, Ecosystems & Environment 159, 145-160.

Lusiana, B., Van Noordwijk, M., Johana, F., Galudra, G., Suyanto, S., Cadisch, G., 2014. Implications of uncertainty and scale in carbon emission estimates on locally appropriate designs to reduce emissions from deforestation and degradation (REDD+). Mitigation and Adaptation Strategies for Global Change 19, 757-772.

Luo, P., He, J.J., Yao, Y.L., Dai, X.H., Cheng, R.X., Wang, L.F., 2012. Differential responses of two rubber tree clones to chilling stress. African Journal of Biotechnology 11, 13466-13471.

Lü, X. T., Tang, J. W., He, Y. C., Duan, W. G., Song, J. P., Xu, H. L., and Zhu, S. Z., 2007. Biomass and its allocation in tropical seasonal rain forest in Xishuangbanna, Southwest China. Journal of Plant Ecology 31, 11-22. (in Chinese).

MacFarlane, D.W., Kuyah, S., Mulia, R., Dietz, J., Muthuri, C., Van Noordwijk, M., 2014. Evaluating a non-destructive method for calibrating tree biomass equations derived from tree branching architecture. Trees 28, 807-817

Maeght, J.-L., Rewald, B., Pierret, A., 2013. How to study deep roots- and why it matters. Frontiers in Plant Science 4, 299. doi: 10.3389/fpls.2013.00299

Maeght, J.-L., Gonkhamdee, S., Ayutthaya, S.I.N., Stokes, A., Pierret., A., 2015. Seasonal patterns of fine root production and turnover in a mature rubber tree (*Hevea brasiliensis* Müll. Arg.) stand-differentiation with soil depth and implications for soil carbon stocks. Frontiers in Plant Science 6, 1022. doi: 10.3389/fpls.2015.01022.

Malhi, Y., Grace, J., 2000. Tropical forests and atmospheric carbon dioxide. Trends in Ecology & Evolution 15, 332-337.

Mann, C.C., 2009. Addicted to rubber. Sience 325, 564-566.

Markum, Arisoesilaningsih, E., Suprayogo, D.,Hairiah, K., 2013. Plant species diversity in relation to carbon stocks at Jangkok watershed, Lombok island. AGRIVITA. 35, 1-11.

Marohn, C., Schreinemachers, P., Quang, D.V., Berger, T., Siripalangkanont, P., Nguyen, T.T., Cadisch, G., 2013. A software coupling approach to assess low-cost soil conservation strategies for highland agriculture in Vietnam. Environmental Modelling & Software. 45, 116-128.

Medlyn, B.E., Barrett, D.J., Landsberg, J.J., Sands, P., Clement, R., 2003. Conversion of canopy intercepted radiation to photosynthate: modeling approaches at regional scales. Functional Plant Biology 30,153-169.

Medlyn, B.E., Duursma, R.A., Zeppel, M.J.B., 2011. Forest productivity under climate change: a checklist for evaluating model studies. Wiley Interdisciplinary Reviews.Climate Change 2, 332-355.

Meti, S., Meerabai, M., Salam, M.A., Jacob, J., Vijayaraghavakumar, 2014. Soil nutrient dynamics of mature rubber (*Hevea brasiliensis* Müll. Arg.) plantation in relation to phenology and growing environment. Journal of the Indian Society of Soil Science 62, 376-383.

Min,S., Huang, J.K., Waibel, H. 2017. Rubber specialization vs crop diversification: the roles of perceived risks. China Agricultural Economic Review 9, 188-210.

Mo, X. X., Zhu, H., Zhang, Y. J., Ferry Slik, J. W., Liu, J. X., 2011. Traditional forest management has limited impact on plant diversity and composition in a tropical seasonal rainforest in SW China. Biological Conservation 144, 1832-1840.

Mokany, K., Raison, R. J., Prokushkin, A. S., 2006. Critical analysis of root: shoot ratios in terrestrial biomes.Global Change Biology 12, 84-96.

Monserud, R.A., 2003. Evaluating forest models in a sustainable forest management context. Forest Biometry, Modelling and Information Science 1, 35–47.

Moraes, V.H.F., 1977. Rubber. In *Ecophysiology of Tropical Crops* (P. de T. Alvin and T.T. Kozlowski, Eds.), Academic press, New York. pp. 315-331

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747-756.

Munasinghe, E.S., Rodrigo, V.H.L., Gunawardena, U.A.D.P., 2014. Modus operandi in assessing biomass and carbon in rubber plantations under varing climatic conditions. Experimental Agriculture 50, 1-19.

Murray, J.P., Grenyer, R., Wunder, S., Raes, N., Jones, J.P.G., 2015. Spatial patterns of carbon, biodiversity, deforestation threat, and REDD+ projects in Indonesia. Conservation Biology 5, 1434–1445

Myers, E.C., 2007. Policies to reduce emissions from deforestation and degradation (REDD) in tropical forests: An examination of the issues facing the incorporation of REDD into market-based climate policies. Discussion paper. Resources for the Future, Washington, D.C. http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-07-50.pdf. Accessed on-line June 2016

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Naji, H.R., Sahri, M.H. 2012. Intra- and inter-clonal tree growth variations of *Hevea brasiliensis*. Journal of Forest Research 23(3), 429-434

Naji, H.R., Sahri, M.H., Nobuchi, T., Bakar, E.S., 2011. The effect of growth rate on wood density and anatomical characteristics of Rubber wood (*Hevea brasiliensis* Muell. Arg.) in two different clonal trails. Journal of Natural Product and Plant Resources 1, 71-80

Nelson, D.W., and Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page AL (ed) Methods of soil analysis II. American Society of Agronomy, Madison, pp. 539-579.

Nguyen, B.T., 2013. Large-scale altitudinal gradient of natural rubber production in Vietnam. Industrial Crops and Products 41, 31-40.

Nguyen, B.T., Dang, M.K., 2016. Temperature dependence of natural rubber productivity in the southeastern Vietnam. Industrial Crops and Products 83, 24-30.

Nguyen, T. T., Verdoodt, A., Tran, V. Y., Delbecque, N., Tran, T. C., Ranst, E. V., 2015. Design of a GIS and multi-criteria based land evaluation procedure for sustainable land-use planning at the regional level. Agriculture, Ecosystems & Environment 200, 1-11.

Nizami, S. M., Zhang, Y. P., Sha, L. Q., Zhao, W., Zhang, X., 2014. Managing carbon sinks in rubber (*Heveabrasilensis*) plantation by changing rotation length in SW China. PLoS ONE. 9, 12.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K., 2001. Terrestrial ecoregions of the world: a new map of life on earth. Bioscience 51, 933-938

O'Neill, R. V., 1989. Perspectives in hierarchy and scale. - In: Roughgarden, J., May, R. M. and Levin, S. A. (eds), Perspectives in ecological theory. Princeton Univ. Press, Princeton, NJ, pp. 140-156

Palm, C.A., Woomer, P., Alegre, J., Arévalo, L., Castilla, C., Cordeiro, D.G., Feigl, B., Hairiah,K., Kotto-Same, J., Mendes, A., 2000. Carbon Sequestration and Trace Gas Emissions in Slash-And-Burn and Alternative Land Uses in the Humid Tropics Climate Change Working Group Final Report, Phase II C. Palm. Nairobi, Kenya.

Palm, C. A., van Noordwijk, M., Woomer, P. L., Alegre, J. C., Arévalo, L., Castilla, C. E., Cordeiro, D. G., Hairiah, K., Kotto-Same, J., Moukam, A., Parton, W. J., Rice, A., Rodrigues, V., Sitompul, S. M. 2005. Carbon Losses and Sequestration Following Land Use Change in the Humid Tropics. Slash and Burn: The Search for Alternatives. New York, USA, Columbia University Press. pp 45-63.

Paine, C.E.T., Marthews, T.R., Vogt, D.R., Purves, D., Rees, M., Hector, A., Turnbull, L.A., 2012. How to fit nonlinear plant growth models and calculate growth rates: an update for ecologists. Methods in Ecology and Evolution 3, 245-256.

Park, B.B., Yannai, R.D., Vadeboncoeur, M.A., Hamburg, S.P., 2007. Estimating root biomass in rocky soils using pits, cores, and allometric equations. Soil Science Society of America Journal 71, 206-213.

Pang, J. P., Chen, M. Y., Tang, J. W., 2009. Plant growth dynamic, and the soil moisture and nutrients change in a Heava-Flemingia agroforestry system in Xishuangbanna, SW of China. Journal of Mountain Science 4, 433-441.

Pearson, T., Walker, S. and Brown, S. 2005. Sourcebook for land use, land-use change and forestry projects. Winrock International and the World Bank Biocarbon Fund. 29pp

Perfecto, I. and Vandermeer, J. 2010. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. Proceedings of the National Academy of Sciences.

Petsri, S., Chidthaisong, A., Pumijumnong, N., Wachrinrat, C., 2013. Greenhouse gas emissions and carbon stock changes in rubber tree plantations in Thailand from 1990 to 2004. Journal of Cleaner Production 52, 61-70.

Picard, N., Saint-André, L., Henry, M., 2012. Mannual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier, p. 215.

Priyadarshan, P.M., 2003. Breeding *Hevea Brasiliensis* for environmental constrains. Advances in Agronomy 79, 351–400.

Priyadarshan, P.M., 2017. Biology of Hevea Rubber. Springer, Berlin. 251p.

Priyadarshan, P.M., Hoa, T.T.T., Huasun, H., de Goncalves, P.S., 2005. Yielding potential of rubber (*Hevea brasiliensis*) in sub-optimal environments. Journal of Crop Improvement 14, 221-247.

Priyadarshan, P.M., Sasikumar, S., 2001. Phenological changes in *Hevea brasiliensis* under differential geo-climates. Plant. Kuala Lumpur 77, 447-459.

Priyadarsini, R., 1999. Estimasi Modal C (C-stock) MasukanBahanOrganik, danHubungannyadenganPopulasiCacing Tanah padaSistemWannatani. Program PascaSarjana, UniversitasBrawijaya, Malang. pp.76.

Purnamasari R., Cahco O., Simmons, P. 2002. Management strategies for Indonesian rubber production under yield and price uncertainty: a bioeconomic analysis. Agroforestry Systems 54, 121-135.

Qi, D.L., Zhou, J.N., Xie, G.S., Wu, Z.X., 2016. Optimizing Tapping-Tree Density of Rubber (*Hevea brasiliensis*) Plantations in South China. Small-scale Forestry 15, 61-72.

Qureshi, A., Pariva, Badola, R., Hussain, S. A., 2012. A review of protocols used for assessment of carbon stock in forested landscapes. Environmental Science & Policy 16, 81-89.

R Development Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Available in https://www.r-project.org/.

Rakchum, P., 2010. "Physiological Responses, Latex Yield and latex Biochemical Component of the Rubber tree (Hevea brasiliensis) under Irrigation Management," M.S. thesis, Prince of Songkla University, Hat Yai, Thailand.

Ranjitkar, S., Sujakhu, N.M., Lu, Y., Wang, Q., Wang, M., He, J., Mortimer, P.E., Xu, J. C., Kindt, R., Zomer, R.J. 2016. Climate modelling for agroforestry species selection in Yunnan. Environmental Modelling & Software 75, 262-272.

Rao, P.S., Saraswathyamma, C.K., Sethuraj, M.R., 1998. Studies on the relationship between yield and meteorological parameters of para rubber tree (*Hevea brasiliensis*). Agricultural and Forest Meteorology 90, 235-245.

Raj, S., Das, G., Pothen, J., Dey, S.K., 2005. Relationship between latex yield of

Hevea brasiliensis and antecedent environmental parameters. International Journal of Biometeorology 49,189-196

Ramirez, J., Jarvis, A., 2010. Downscaling global circulation model outputs: The delta method decision and policy analysis working paper no. 1. International Center for Tropical Agriculture. Cali, Colombia

Reich, P.B., 1995. Phenology of tropical forests: patterns, causes, and consequences. Canadian Journal of Botany 73, 164-174.

Reich, P.B., Borchert, R. 1984. Water stress and tree phenology in a tropical dry forest in the lowlands of Costa Rica. Journal of Ecology 72, 61-74.

Reidsma, P., Ewert, F., Oude Lansink, A. and Leemans, R. 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. European Journal of Agronomy 32, 91-102.

Reyer, C., 2013. The Cascade of Uncertainty in Modelling Forest Ecosystem Responses to Environmental Change and the Challenge of Sustainable Resource Management Mathematisch-Naturwissenschaftliche Fakultät II Humboldt Universität, Berlin, pp. 168.

Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., Pilz, T. 2014. Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. Annuals of Forest Science 71, 211–225

Riahi, K., Gruebler, A., Nakicenovic N. 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 887-935.

Ritchie, J.T.1991. Wheat phasic development. In Hanks and Ritchie (ed.) Modeling Plant and Soil Systems. Agronomy Monograph 31, ASA, CSSSA, SSSA, Madison, WI. pp. 31-54.

Rodríguez-Loinaz, G., Amezaga, I., Onaindia, M., 2013. Use of native species to improve carbon sequestration and contribute towards solving the environmental problems of the timberlands in Biscay, northern Spain. Journal of Environmental Management 120, 18-26.

Rojo-Martínez, G.E., Jasso-Mata, J., Vargas-Hernández, J.J., Palma-López, D.J., Velázquez-Martínez, A., 2005. Aerial biomass in commencial rubber plantations (*Hevea brasiliensis* Müll. Arg.) in the state of Oaxaca, México. Agrociencia 39, 449-456.

Roy, S., Choudhury, M., Eappen, T., Chakraborty, S.K., Dey, S.K., 2005. Effect of planting density and fertilisers on growth and early yield of rubber in Tripura. Indian Journal of Natural Rubber Research 18, 81–86.

Ruimy, A., Kergoat, L., Bondeau, A., The participants of the Potsdam NPP model Intercomparison. 1999. Comparing global models of terrestrial net primary productivity (NPP): Analysis of differences in light absorption and light-use efficiency. Global Change Biology 5 (Suppl.1), 56-64

Running, S.W., Hunt, E.R. Jr., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME–BGC, and an application for global-scale models. In: Ehleringer, J.R., Field, C.B. (eds) Scaling physiological processes:

leaf to globe. Academic Press, San Diego, pp 141-157.

Saengruksawong, C., 2012. Growths and carbon stocks of Para rubber plantations on phonpisai soil series in Northeastern Thailand. Rubber Thai Journal 1, 1-18.

Salvini, G., Ligtenberg, A., van Paassen, A., Bregt, A.K., Avitabile, V., Herold, M., 2016. REDD+ and climate smart agriculture in landscapes: a case study in Vietnam using companion modeling. Journal of Environmental Manage 172, 58-70.

Samarappuli, L., 2000. Rubber growing soils and their characteristics. Bulletin of the Rubber Research Institute of Sri Lanka 41, 10-21.

Sánchez-Salguero, R., Camarero, J.J., Gutiérrez, E., Rouco, F.G., Gazol, A., Sangüesa-Barreda, G., Andreu-Hayles, L., Linares, J.C., Seftigen, K., 2017. Assessing forest vulnerability to climate warming using a process-based model of tree growth: bad prospects for rear-edges. Global Change Biology 23, 2705-2719.

Sands, P.J., Battaglia, M., Mummery, D., 2000. Application of process-based models to forest management: experience with PROMOD, a simple plantation productivity model. Tree Physiology 20, 383-392.

Sands, P.J. and Landsberg, J.J., 2002. Parameterisation of 3-PG for plantation grown Eucalyptus globulus. Forest Ecology and Management 163, 273-292.

Satheesh, P.R., Jacob, J., 2011. Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. Nat. Rubber Res. 24, 1-9.

Sayer, J., Sunderland, T., Ghazoul, J., Pfund, J. L., Sheil, D., Meijaard, E., Venter, M., Boedhihartono, A.K., Day, M., Garcia, C., van Oosten, C. and Buck, L E. 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proceedings of the national academy of sciences 110, 8349-8356.

Schelhaas, M.J., van Esch, P.W., Groen, T.A., de Jong, B.H.J., Kanninen, M., Liski, J., Masera, O., Mohren, G.M.J., Nabuurs, G.J., Palosuo, T., Pedroni, L., Vallejo, A., Vilén, T. 2004 CO2FIX V 3.1–a modelling framework for quantifying carbon sequestration in forest ecosystems. ALTERRA Report 1068. Wageningen.

Schroth, G., D' Angelo, S.A., Teixeira, W.G., Haag, D., Lieberei, R., 2002. Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years. Forest Ecology and Management 163, 131-150.

Sdoodee, *S. and* Rongsawat. *S. 2012.* Impact of climate change on smallholders' rubber production in Songkhla province, southern Thailand. Paper presented at the 2012 International and National Conference for the Sustainable Community Development of "Local Community: The Foundation of Development in the ASEAN Economic Community (AEC)", Khon Kaen, Thailand

Seely, B., Welham, C., Scoullar, K. 2015. Application of a hybrid forest growth model to evaluate climate change impacts on productivity, nutrient cycling and mortality in a montane forest ecosystem. PLoS ONE 10, e0135034

Seidl, R., Eastaugh, C.S., Kramer, K., Maroschek, M., Reyer, C., Socha, J., Vacchiano, G., Zlatanov, T., Hasenauer, H., 2013. Scaling issues in forest ecosystem management and how to address them with models. European Journal of Forest Research 132,653-666.

Seidl, R., Rammer, W., Scheller, R.M., Spies, T.A., 2012. An individual-based process model to simulate landscape scale forest ecosystem dynamics. Ecological Modelling 231, 87-100.

Senevirathna, A.M.W.K., Wilbert, S., Perera, S.A.P.S., Wijesinghe, A.K.H.S., 2007. Can tapping panel dryness of rubber (*Hevea brasiliensis*) be minimised at field level with better management. Journal of the Rubber Research Institute of Sri Lanka 88, 77-87.

Senf, C., Pflugmacher, D., van der Linden, S., Hostert, P., 2013. Mapping rubber plantations and natural forests in Xishuangbanna (Southwest China) Using multi-spectral phenological metrics from MODIS time series. Remote Sensing 5, 2795-2812.

Shao, Z. and Hu, Z., 1984. Powdery mildew infestation investigation on different leaf phenologies of rubber trees Yunnan. Tropical Technology 1-5.

Shao, Z., Zhou, J., Chen, J., Li, C., Meng, Y., 1996. Powdery mildew epidemic rate of rubber trees Yunnan. Tropical Technology 2-12.

Shorrocks, V.M., Templeton, J.K., Iyer, G.C., 1965. Mineral nutrition, growth and nutrient cycle of Hevea brasiliensis III. The relationship between girth and shoot dry weight. Journal of the Rubber Research Institute of Malaysia 19, 85-92.

Shuogang, A., Yagang, G., 1990. Extrapolation of the high yield physiological regulation of Hevea brasiliensis in Xishuangbanna. In: Proceedings Of the IRRDB Symposium on Physiology and Exploitation of *Hevea brasiliensis*, pp. 83–92.

Silpi, U., Thaler, P., Kasemsap, P., Lacointe, A., Chantuma, A., Adam, B., Gohet Thaniswanyankura, E.S., Améglio, T., 2006. Effect of tapping activity on the dynamics of radial growth of *Hevea brasiliensis* trees. Tree Physiology 26 (12), 1579–1587.

Silpi, U., Lacointe, A., Kasempsap, P., Thanysawanyangkura, S., Chantuma, P., Gohet, E., Musigamart, N., Clément, A., Améglio, T., Thaler, P., 2007. Carbohydrate reserves as a competing sink: evidence from tapping rubber trees. Tree Physiology 27, 881–889. https://doi.org/10.1093/treephys/27.6.881

Smith, S.J. and Wiglegy, T.M.L. 2006. Multi-Gas Forcing Stabilization with the MiniCAM. Energy Journal 27, 373-391.

Snowdon, P., Raison, J., Keith, H., Ritson, P., Grierson, P., Adams, M., Montagu, K., Bi, H.Q., Burrows, W., Eamus, D., 2002. Protocol for sampling tree and stand biomass. National Carbon Accounting System Technical Report No. 31. Canberra: Australian Greenhouse Office.

Sone, K., Watanabe, N., Takase, M., Hosaka, T., Gyokusen, K., 2014. Carbon sequestration, tree biomass growth and rubber yield of PB260 clone of rubber tree (*Hevea brasiliensis*) in North Sumatra. Journal of Rubber Research 17, 115-127.

Song, Q.H., Zhang, Y.P., 2010. Biomass, carbon sequestration and its potential of rubber plantations in Xishuangbanna, Southwest China. Chinese Journal of

Ecology 29, 1887-1891. (in Chinese).

Song, Q. H., Tan, Z. H., Zhang, Y. P., Sha, L. Q., Deng, X. B., Deng, Y., Zhou, W. J., Zhao, J. F., Zhao, J. B., Zhang, X., Zhao, W., Yu, G. R., Sun, X. M., Liang, N. S., Yang, L. Y., 2014. Do the rubber plantations in tropical China act as large carbon sinks? iForest 7, 42-47.

Sopharat, J., Gay, F., Thaler, P., Sdoodee, S., Ayutthaya, S.I.N., Tanavud, C., Hammecker, C., Do, F.C., 2014. A simple framework to analyze water constraints on seasonal transpiration in rubber tree (*Hevea brasiliensis*) plantations. Frontiers in Plant Sciences 5, 1-11.

Spitters, C.J.T., Van Keulen, H., Van Kraalingen, D.W.G., 1989. A simple and universal crop growth simulator: SUCROS87. In: Rabbinge R, Ward SA, van Laar HH, eds. Simulation and systems management in crop protection. Wageningen: Pudoc, pp. 147-81.

Stigler, G.J., 1987. The theory of price, (4th ed). New York, USA: Macmillan

Supit, I. 2003. Updated system description of the WOFOST crop growth simulation model as implemented in the crop growth monitoring system applied by the European Commission. Treemail Publishers, Heelsum, The Netherlands. (Access through http://www.treemail.nl/download/treebook7/start.htm)

Suratman, M. N., Bull, G. Q., Leckie, D. G., Lemay, V. M., Marshall, P. L., Mispan, M. R., 2004. Prediction models for estimating the area, volume, and age of rubber (*Heveabrasiliensis*) plantations in Malaysia using Landsat TM data. International Forestry Review 6, 1-12.

Sun, J., Cheng, G.W., Li, W.P., 2013. Meta-analysis of relationships between environmental factors and aboveground biomass in the alpine grassland on the Tibetan Plateau. Biogeosciences 10, 1707-1715.

Tao, G.D., 1989. Vegetation survey of Nabanhe basin. In: Investigation Group of Nabanhe Watershed Nature Reserve, Synthetical Investigation Report of Nabanhe Watershed Nature Reserve. Environmental Monitoring Station Press of Xishuangbanna, Xishuangbanna. pp. 18-31.

Tan, Z. H., Zhang, Y. P., Song, Q. H., Liu, W. J., Deng, X. B., Tang, J. W., Deng, Y., Zhou, W. J., Yang, L. Y., Yu, G. R., Sun, X. M., Liang, N. S., 2011. Rubber plantations act as water pumps in tropical China. Geophysical Research Letters 38, 1-3.

Tang, J. W., Pang, J. P., Chen, M. Y., Guo, X. M., Zeng, R., 2009. Biomass and its estimation model of rubber plantations in Xishuangbanna, Southwest China. Chinese Journal of Ecology 28, 1942-1948. (in Chinese).

Tang, J.W., Yin, J.X., Qi, J.F., Jepsen, M.R., Lü, X.T., 2012. Ecosystem carbon storage of tropical forests over limestone in Xishuangbanna, SW China. Journal of Tropical Forest Science 24, 399-407.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93, 485–498.

Thellmann, K., Blagodatsky, S., Häuser, I., Liu, H.X., Wang, J., Asch, F., Cadisch, G., Cotter, M. 2017. Assessing ecosystem services in rubber dominated landscapes in South-East Asia- a challenge for biophysical modelling and transdisciplinary valuation. 2017. Forests 8, 505. https://doi.org/10.3390/f8120505

Tjeuw, J., Mulia, R., Slingerland, M., Van Noordwijk, M., 2015. Tree or shrub: a functional branch anlaysis of *Jatropha curcas* L. Agroforestry Systems 89, 841-856

Tripathi, A., Singh, G.S. 2013. Perception, anticipation and responses of people to changing climate in the Gangetic Plain of India. Current Science 105, 1673–1684.

Turner, D. P., Winjum, J. K., Kolchugina, T. P., Vinson, T. S., Schroeder, P.E., Phillips, D. L., Cairns, M. A. 1998. Estimating the terrestrial carbon pools of the former Soviet Union, conterminous US, and Brazil. Climate Research 9, 183-196.

UNESCO. 1996. Biosphere, reserves, the Seville strategy and the statutory framework of the world network. Man and the Biosphere Programme, UNESCO, Paris, France. pp.18

Van Laake, P.E. and Sanchez-Azofeifa, G.A., 2004. Simplified atmospheric radiative transfer modelling for estimating incident PAR using MODIS atmosphere products, Remote Sensing of Environment 91, 98-113.

Van Laake, P.E. and Sanchez-Azofeifa, G.A., 2005. Mapping PAR using MODIS atmosphere products, Remote Sensing of Environment 94, 554-563.

Van Noordwijk, M., Leimona, B., Jindal, R., Villamor, G.B., Vardhan, M., Namirembe, S., Catacutan, D., Kerr, J., Minang, P.A., Tomich, T.P., 2012. Payments for environmental services: evolution toward efficient and fair incentives for multifunctional landscapes. Annual Review of Environment and Resources 37, 389-420

Van Noordwijk, M., Lusiana, B., 1999. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Systems 43, 217-242.

Van Noordwijk, M., Lusiana, B., Khasanah, N., Mulia, R., 2011. WaNuLCAS version 4.0, Background on a model of water nutrient and light capture in agroforestry systems. Bogor, Indonesia. World Agroforestry Centre – ICRAF, SEA Regional Office, 224 p.

Van Noordwijk, M., Suyamto, D. A., Lusiana, B., Ekadinata, A., Hairiah, K., 2008. Faciliating agroforestation of landscapes for sustainable benefits: tradeoffs between carbon stocks and local development benefits in Indonesia according to the FALLOW model. Agriculture, Ecosystems & Environment 126, 98-112.

Van Noordwijk, M., Rahayu, S., Hairiah, K., Wulan, Y. C., Farida, A., Verbist, B., 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. Sci. China (Series C). 45 Supp., 75-86.

Van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S., van Houdt, R. 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climate Change 81, 119-159.

VEMAP Members. 1995. Vegetation/Ecosystem Modeling and Analysis Project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. Global Biogeochemical Cycles 9, 407- 437

Venkatachalam, P., Geetha, N., Sangeetha, P., Thulaseedharan, A., 2013. Nature rubber producing plants: an overview. African Journal of Biotechnology 12, 1297-1310.

Villamor, G.B., Le, Q.B., Djanibekov, U., Van Noordwijk, M., Vlek, P.L.G., 2014. Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra. Environmental Modelling & Software. 61, 151-165.

Vongkhamheng, C., Zhou, J.H., Beckline, M., Phimmachanh, S. 2016. Socioeconomic and Ecological Impact Analysis of Rubber Cultivation in Southeast Asia. Open Access Library Journal 3, e2339. http://dx.doi.org/10.4236/oalib.1102339

Walker, E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P., von Krauss, M.P. K., 2003. Defining uncertainty. A conceptual basis for uncertainty management in model based decision support. Integrated Assessment 4, 5-17

Wang, J., Aenis, T., Hofmann-Souki, S. 2018. Triangulation in participation: Dynamic approaches for science-practice interaction in land-use decision making in rural China. Land Use Policy 72, 364-371

Wang, W.F., Wei, X.H., Liao, W.M., Blanco, J.A., Liu, Y.Q., Liu, S.R., Liu, G.H., Zhang, L., Guo, X.M., Guo, S.M., 2013. Evaluation of the effects of forest management strategies on carbon sequestration in evergreen broad-leaved (*Phoebe bournei*) plantation forests using FORECAST ecosystem model. Forest Ecology and Management 300, 21-32.

Warren-Thomas, E., Dolman, P.M., Edwards, D.P., 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. Conservation Letters. 8, 230-241

Warren-Thomas, E.M., Edwards, D.P., Bebber, D.P., Chhang, P., Diment, A.N., Evans, T.D., Lambrick, F.H., Maxwell, J.F., Nut, M., O'Kelly, H.J., Theilade, I., Dolman, P.M., 2018. Protecting tropical forests from the rapid expansion of rubber using carbon payments. Nature Communications 9, 911.

Wasana, C.M.A.P., 2010. An approach for estimating area of rubber plantation: integrating satellite and physical data over the Northeast Thailand, In: Proceedings of the 31st Asian Conference on Remote Sensing Vietnam, Hanoi, Vietnam

Wang, L.F., 2014. Physiological and molecular responses to drought stress in rubber tree (Hevea brasiliensis Muell. Arg.). Plant Physiology and Biochemistry 83, 243-249.

Wang, W., Peng, C., Kneeshaw, D.D., Larocque, G.R., Song, X., Zhou, X., 2012. Quantifying the effects of climate change and harvesting on carbon dynamics of boreal aspen and jack pine forests using the TRIPLEX-Management model. Forest Ecology and Management 281, 152-162

Wauters, J. B., Coudert, S., Grallien, E., Jonard, M., Ponette, Q., 2008. Carbon stock in rubber tree plantations in Western Ghana and Mato Grosso (Brazil). Forest Ecology and Management 255, 2347-2361.

Widayati, A., Suyanto, van Noordwijk, M., 2011. Towards Reduced Emissions in a High-Stake District REALU Project Design for TanjungJabung Barat (Tanjabar), Jambi, Indonesia. World Agroforestry Centre, Bogor. pp.148

Wise, M.A., Calvin, K.V., Thomson, A.M., Clarke, L.E., Bond-Lamberty, B., Sands, R.D., Smith, S.J., Janetos, A.C., Edmonds, J.A. 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183-1186.

Wu, J.G., Jones, K.B., Li, H.B., Loucks, O.L. 2006. Scaling and uncertainty analysis in Ecology. Methods and applications. Published by Springer, P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Wu, Z.L., Liu, H.M., Yun, L.L., 2001. Rubber cultivation and sustainable development in Xishuangbanna, China. International Journal of Sustainable Development & World Ecology 8, 337-345.

Xiao, C., 2010. Comparative studies of comprehensive prevention and control for rubber powdery mildew China. Tropical Technology 56-58.

Xie, J., Li, Y. M., Hou, T. C., 2012. Integrated soil fertility quality analysis under different land use types in Naban river watershed. Journal of Yunnan Agricultural University 27, 401-407. (in Chinese).

Xu, J. C., 2011. China's new foresters aren't as green as they seem. Nature. 477, 371.

Xu, J. C., Fox, J., Vogler, J. B., Zhang, P. F., Fu, Y. S., Yang, L. X., Jie, Q., Leisz., S. 2005. Land-use and land-cover change and farmer vulnerability in Xishuangbanna prefecture in southwestern China. Environmental Management 36, 404-413.

Xu, J. C., Grumbine, R. E.,Beckschäfer, P., 2014. Landscape transformation through the use of ecological and socioeconomic indicators in Xishuangbanna, Southwest China, Mekong Region. Ecological Indicators 36, 749-756.

Xu, J. C., Lebel. L., Sturgeon, J., 2009. Functional links between biodiversity, livelihoods, and culture in a Hani Swidden Landscape in Southwest China. Ecology and Society 14, 20

Xu, J. T., Yin, R. S., Li, Z., Liu, C., 2006. China's ecological rehabilitation: unprecedented efforts,dramatic impacts, and requisite policies. Ecological Economics 57, 595-607.

Xu, Q. X. 1988. Analysis the relationship temperature, heat with rubber tree's yield and the northward temperature index of rubber. Guangxi Tropical Agriculture 1, 9-16 (in Chinese)

Xu, W. R., Ma, Y. X., Li, H. M., Liu, W. J., 2011. Estimating biomass for rubber plantations in Xishuangbanna using remote sensing data. Journal of Yunnan University 33, 317-323. (in Chinese).

Yanai, R.D., Battles, J.J., Richardson, A.D., Rastetter, E.B., Wood, D.M., Blodgett, C., 2010. Estimating uncertainty in ecosystem budget calculations. Ecosystems 13, 239-248

Yang, J.C., Huang, J.H., Pan, Q.M., Tang, J.W., Han, X.G., 2004. Long-term impacts of land-use change on dynamics of tropical soil carbon and nitrogen pools.

Journal of Environmental Sciences 16, 256-261.

Yang, X.Q., Blagodatsky, S., Lippe, M., Liu, F., Hammond, J., Xu, J.C., Cadisch, G., 2016. Land-use change impact on time-averaged carbon balances: Rubber expansion and reforestation in a biosphere reserve, South-West China. Forest Ecology and Management 372, 149-163.

Yang, X.Q., Blagodatsky, S., Liu, F., Beckschäfer, P., Xu, J.C., Cadisch, G., 2017. Rubber tree allometry, biomass partitioning and carbon stocks in mountainous landscapes of sub-tropical China. Forest Ecology and Management 404, 84-99.

Yeang, H.Y., 2007. Synchronous flowering of the rubber tree (*Hevea brasiliensis*) induced by high solar radiation intensity. New Phytologist 175, 283-289.

YEPB. 2006. Nabanhe national nature reserve in Xishuangbanna. Yunnan Science and Technology Press, Kunming.

Yi, Z. F., Wong, G., Cannon, C. H., Xu, J. C., Beckschäfer, P., Swetnam, R. D., 2014a. Can carbon-trading schemes help to protect China's most diverse forest ecosystems? A case study from Xishuangbanna, Yunnan. Land Use Policy. 38, 646-656.

Yi, Z.F., Cannon, C.H., Chen, J., Ye, C.X., Swetnam, R.D., 2014b. Developing indicators of economic value and biodiversity loss for rubber plantations in Xishuangbanna, Southwest China: a case study from Menglun township. Ecological Indicators 36, 788-797.

Yoshino, M., 1990. Problems in climates and agroclimates for mountain developments in Xishuangbanna, South Yunnan, China. Geographical review of Japan 2, 149-160.

Yousefpour, R., Jacobsen, J.B., Thorsen, B.J., Meilby, H., Hanewinkel, M., Oehler, K., A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. Annals of Forest Science 69, 1-15

Yousefpour, *R.,* Temperli, *C.,* Bugmann, *H.,* Elkin, *C.,* Hanewinkel, *M.,* Meilby, *H.,* Jacobsen, J.B., Thorsen, B.J., *2013.* Updating beliefs and combining evidence in adaptive forest management under climate change: a case study of Norway spruce (Picea abies L. Karst) in the Black Forest, Germany. J*ournal of* Environ*mental Management* 122, 56-64.

Yu, H.Y., Hammond, J., Ling, S.H., Zhou, S.X., Mortimer, P.E., Xu, J.C., 2014. Greater diurnal temperature difference, an overlooked but important climatic driver of rubber yield. Industrial Crops and Products 62, 14-21.

Yu, W., Zhang, M.L., Mai, Q.F., Jiang, J.S., 2006. Damage of Typhoon Damrey to the rubber industry in Hainan State Farm Bureau and its countermeasures for future development. Chinese Journal of Tropical Agriculture. 26, 41-43 (in Chinese)

Yuen, J. Q., Ziegler, A. D., Webb, E. L., Ryan, C. M., 2013. Uncertainty in below-ground carbon biomass for major land covers in Southest Asia. Forest Ecology and Management 310, 915-926.

Yuen, J.Q., Fung, T., Ziegler, A.D., 2016. Review of allometric equations for major land covers in SE Asia: Uncertainty and implications for above- and below-ground carbon estimates. Forest Ecology and Management360, 323-340.

Yunnan Institute of Tropical Crops .1981. Rubber powdery mildew forecasting in Jinghong Yunnan. Tropical Technology 28-34.

Zavala, M.A., Ruiz-Benito, P., Vacchiano, G, Lines, E.R., Reyer, C., Ratcliffe, S., Morin, X., Hartig, F., Mäkelä, A., Yousefpour, R., Palacios, A., Benito-Garzón, M., Morales-Molino, C., Camarero, J.J., Jump, A.S., Lehtonen, A., Ibrom, A., Owen, H.J.F., 2017. Assessing European forest vulnerability in response to climate change: do we need more data or better models? In: PROFOUND Final Conference: Robust projections of forests under climate change – data, methods and models, Potsdam Institute of Climate Change. Germany.

Zeide, B., 1993. Analysis of growth equations. Forest Science 39, 594–516

Zeng, Y., Yanping, Y. (Eds.), 2004. Theory and Application for Rubber Plants in Highlands and North-Edge Tropical Yunnan. The Ministry of Land Reclamation of Yunnan, Yunnan, pp. 236–249.

Zhai, D.L., Cannon, C.H., Ferry Slik J.W., Zhang, C.P., Dai, Z.C. 2012. Rubber And Pulp Plantations Represent A double threat To Hainan's natural tropical forests. Journal of Environmental Management 96, 64-73.

Zhai, D.L., Dong, J.W., Cadisch, G., Wang, M.C., Kou, W.L., Xu, J.C., Xiao, X.M., Abbas, S., 2018. Comparison of pixel- and object- based approaches in phenology based rubber planation mapping in fragmented landscapes. Remote Sensing 10, 44. https://doi.org/10.3390/rs10010044

Zhai, D. L., Xu, J. C., Dai, Z. C., Cannon, C. H., Grumbine, R. E., 2014. Increasing tree cover while losing diverse natural forests in tropical Hainan, China. Regional Environmental Change 14, 611-621.

Zhang, J. and Cao, M., 1995. Tropical forest vegetation of Xishuang- banna SW China and its secondary changes, with special reference to some problems in local nature conservation. Biological Conservation 73, 225- 238.

Zhang, L.J., Bi, H.Q., Cheng, P.F., Davis, C.J., 2004. Modeling spatial variation in tree diameter–height relationships. Forest Ecology and Management 189, 317–329.

Zhang, M., Chen, Y. G., Yu, C. P., Pan, Z. Q., Fan, D. M., Luo, Y. P., Wang, X. C., 2013. Dynamic assessments of plant biomass and carbon storage during the production cycle of tea gardens. Journal of Zhejiang University (Agriculture and Life Sciences) 39, 687-694. (in Chinese).

Zhang, M., Fu, X.H., Feng, W.T., Zou, X.M., 2007. Soil organic carbon in pure rubber and tea-rubber plantations in South-western China. Tropical Ecology 48, 201-207.

Zhang, Y.S., Gao, R.Q., Zhao, Y.K., Feng, S.H., Wang, H.Q., Ratnasingam, J., Lu, J.X., Ye, K.L., 2009. The Rubberwood Utilization in China. In: Rubberwood in China- Resource, market and processing technologies. Research Institute of Wood Industry (CRIWI) and Chinese Academy of Forestry (CAF), Beijing.

Zheng, Z., Feng, Z.L., Cao, M., Liu, H.M., Liu, L.H., 2000. Biomass and net primary production of primary tropical wet seasonal rainforest in Xishuangbanna. Acta Ecologica Sinica 24, 197-203. (in Chinese).

Zhou, Y.F., 2008. Rubber Cultivation in Yunnan. Yunnan University Press, Kunming, pp. 176.

Zhu, H., 2007. On the classification of forest vegetation in Xishuangbanna, southern Yunnan. Acta Botanica Yunnanica 29, 377-387

Zhu, Y.X., Xu, J.C., Li, Q.H., Mortimer, P.E., 2014. Investigation of rubber seed yield in Xishuangbanna and estimation of rubber seed oil based biodiesel potential in Southeast Asia. Energy 69, 834-842.

Ziegler, A.D., Fox, J.M., Xu, J.C., 2009. The rubber juggernaut. Science. 324, 1024-1025

Zomer, R. J., Trabucco, A., Wang, M. C., Lang, R., Chen, H. F., Metzger, M. J., Smajgl, A., Beckschäfer, P., Xu, J. C., 2014. Environmental stratification to model climate change impacts on biodiversity and rubber production in Xishuangbanna, Yunnan, China.Biological Conservation 170, 264-273.

Zongdao, H., Xueqin, Z. 1983. Rubber cultivation in China. In Proceedings of the Rubber Research Institute Malaysia Planters' Conference. Kuala Lumpur, Malaysia. pp. 31-43.

Summary

Rubber plantation has been rapidly expanded in Montane Mainland South East Asia in past decades. Limited by long-term monitoring data availability, the impacts of environmental change on rubber trees carbon stock development still not fully understood. Against global warming background, in order to better facilitate regional forest management, we applied synergetic approach combining field survey and modelling tools to improve predictions of dynamic carbon stock changes. The trade-off analysis regarding to rubber carbon stock and latex production optimization was further discussed in view of sustainable rubber cultivation.

The first study explored the impact of regional land-use changes on landscape carbon balances. The Naban River Watershed National Nature Reserve (NRWNNR), Xishuangbanna, China, was selected as a case study location. Carbon stocks were evaluated using the Rapid Carbon Stock Appraisal (RaCSA) method based on tree, plot, land use and landscape level assessments of carbon stocks, integrating field sampling with remote sensing and GIS technology. The results showed that rubber plantations had larger time-averaged carbon stocks than non-forest land use types (agricultural crops, bush and grassland) but much lower than natural forest. During 23 years (1989-2012), the whole landscape of the nature reserve (26574 ha) gained 0.644 Tg C. Despite rubber expansion, the reforestation activities conducted in NRWNNR were able to enhance the carbon stocks.

Regional evaluation of the carbon sequestration potential of rubber trees depends largely on the selection of suitable allometric equations and the biomass-to-carbon conversion factor. The second study developed generic allometric equations for rubber trees, covering rotation lengths of 4-35 years, within elevation gradient of 621-1,127 m, and locally used rubber tree clones (GT1, PRIM600, Yunyan77-4) in mountainous South Western China. Allometric equations for aboveground biomass (*AGB*) estimations considering diameter at breast height (*DBH*), tree height, and wood density were superior to other equations. We also tested goodness of fit for the recently proposed pan-tropical forest model. The results displayed that prediction of *AGB* by the model calibrated with the harvested rubber tree biomass and wood density was more accurate than the results produced by the pan-tropical forest model adjusted to local conditions. The relationships between *DBH* and height and between *DBH* and biomass were influenced by tapping, therefore biomass and C stock calculations for rubber have to be done using species-specific allometric equations. Based on the analysis of environmental factors acting at the landscape level, we noticed that above- and belowground carbon stocks were mostly affected by stand age, soil clay content, aspect, and planting density. The results of this study provide reference for reliable carbon accounting in other rubber-cultivated regions.

In the last study, we explored how rubber trees growth and production response to climate change and regional management strategies (cultivation elevation, planting density). We applied the process-based Land Use Change Impact Assessment tool (LUCIA) calibrated with detailed ground survey data to model tree biomass development and latex yield in rubber plantations at the tree, plot and landscape level. Model simulation showed that during a 40-year rotation, lowland rubber plantations (< 900m) grew quicker and had larger latex yield than highland rubber (≧900m). High planting density rubber plantations showed 5% higher above ground biomass than those at low- and medium-planting density. The mean total biomass and cumulative latex yield per tree over 40 years increased by 28% and 48%, respectively, when climate change scenarios were modelled from baseline to highest CO_2 emission scenario (RCP 8.5). The same trend of biomass and latex yield increase with climate change was observed at plot level. Denser plantations had larger biomass, but the cumulative latex production decreased dramatically. The spatially explicit output maps produced during modelling could help maximize carbon stock and latex production of regional rubber plantations.

Overall, rubber-based system required for appropriate monitoring scale in both temporal aspect (daily-, monthly-, and yearly-level) and in spatial aspect (pixel-, land use-, watershed-, and landscape- level). The findings from present study highlighted the important application of ecological modelling tools in nature resources management. The lessons learned here could be applicable for other rubber-cultivated regions, by updating with site-specific environmental variables. The significant role of rubber tree not limited in its nature latex production, it also lies in its great carbon sequestration potential. Our results here provided entry point for future developing comprehensive climate change adaption and mitigation strategies in South East Asia. By making use of interdisplinary cooperation, the sustainable rubber cultivation in Great Mekong Regions could be well realized.

Zusammenfassung

In den vergangenen Jahrzehnten wurde der Kautschukanbau in den Bergregionen des südostasiatischen Festlandes rasch ausgebaut. Die Auswirkungen von Umweltveränderungen auf die Entwicklung des Kohlenstoffbestandes von Kautschukbäumen sind durch die eingeschränkte Verfügbarkeit von Langzeit-Monitoring-Daten noch nicht vollständig geklärt. Vor dem Hintergrund der globalen Erwärmung und um die regionale Waldbewirtschaftung zu unterstützen, haben wir einen synergetischen Ansatz angewandt, der Feldmessungen und Modellierungswerkzeuge kombiniert, um die Vorhersage dynamischer Veränderungen der Kohlenstoffbestände zu verbessern. Die Kosten-Nutzen Abwägung für einen nachhaltigen Kautschukanbau bezüglich der Kautschuk-Kohlenstoffvorräte und der Optimierung der Latexproduktion wird im Weiteren diskutiert.

Die erste Studie untersuchte die Auswirkungen regionaler Landnutzungsänderungen auf die Kohlenstoffbilanz der Landschaft. Das Naban River Watershed National Nature Reserve (NRWNNNR), Xishuangbanna, China, wurde als Fallstudienstandort ausgewählt. Die Bewertung der Kohlenstoffvorräte erfolgte mit der Rapid Carbon Stock Appraisal (RaCSA)-Methode. Diese basiert auf der Bewertung von Kohlenstoffvorräten auf dem Niveau von Bäumen, Grundstücken, Landnutzung und Landschaft, mit Einbindung von Feldprobennahme verbunden mit Fernerkundung und GIS-Technologie. Die Ergebnisse zeigten, dass Kautschukplantagen einen größeren zeitgemittelten Kohlenstoffvorrat hatten als nicht-forstliche Landnutzungsarten (Ackerland, Busch- und Grünland), aber viel weniger als natürliche Wälder. Während 23 Jahren (1989-2012) gewann das gesamte Gebiet des Naturschutzgebietes (26574 ha) 0,644 Tg C hinzu. Trotz Ausdehnung der Kautschukanbauflächen konnten die Aufforstungsaktivitäten in NRWNNR die Kohlenstoffvorräte erhöhen.

Die regionale Bewertung des Kohlenstoffsequestrierungspotenzials von Kautschukbäumen hängt wesentlich von der Auswahl geeigneter allometrischer Gleichungen und des Biomasse-Kohlenstoff-Umwandlungsfaktors ab. Die zweite Studie entwickelte allgemeine allometrische Gleichungen für Kautschukbäume, basierend auf Daten aus Kautschukplantagen mit Umtriebszeiten von 4-35 Jahren, Höhenlagen von 621-1.127 m und lokal verwendeten Kautschukbaumklonen (GT1, PRIM600, Yunyan77-4) im bergigen Südwesten Chinas. Allometrische Gleichungen zur Berechnung der oberirdischen Biomasse (AGB), welche den Durchmesser in Brusthöhe (DBH), Baumhöhe und Holzdichte berücksichtigten, waren anderen Gleichungen überlegen. Wir haben auch die Anpassungsgüte des kürzlich vorgeschlagene pan-tropische Waldmodell getestet. Die Ergebnisse zeigten, dass die Vorhersage der AGB durch das mit der destruktiv bestimmten Biomasse und der Holzdichte kalibrierte Modell genauer war als die Ergebnisse des pan-tropischen Waldmodells, das an die lokalen Bedingungen angepasst wurde. Die Beziehungen zwischen DBH und Höhe, und DBH und Biomasse wurden durch die Anzapfung der Bäume beeinflusst. Aufgrund dessen müssen Biomasse- und C-Bestandsberechnungen

für Kautschuk mit artspezifischen allometrischen Gleichungen durchgeführt werden. Basierend auf der Analyse von Umweltfaktoren, die auf Landschaftsebene wirken, stellten wir fest, dass die ober- und unterirdischen Kohlenstoffvorräte vor allem durch das Bestandsalter, den Tongehalt des Bodens, die Hanglage und die Pflanzdichte beeinflusst wurden. Die Ergebnisse dieser Studie liefern Anhaltspunkte für eine zuverlässige Kohlenstoffbilanzierung in anderen Kautschukanbaugebieten.

In der letzten Studie haben wir untersucht, wie Kautschukbäume auf den Klimawandel und regionalen Managementstrategien (Anbauhöhe, Pflanzdichte) reagieren. Wir setzten das prozessbasierte Land Use Change Impact Assessment Tool (LUCIA) ein, das mit detaillierten Bodenuntersuchungsdaten kalibriert wurde, um die Entwicklung der Baumbiomasse und den Latexertrag in Kautschukplantagen auf Baum-, Parzelle- und Landschaftsebene zu modellieren. Die Modellsimulation zeigte, dass während einer 40-jährigen Rotationzeit die Flachland-Kautschukplantagen (< 900m) schneller wuchsen und eine höhere Latexausbeute hatten als die Hochland-Kautschukplantagen (≧900m). Kautschukplantagen mit hoher Pflanzdichte zeigten eine um 5% höhere oberirdische Biomasse als solche mit niedriger und mittlerer Pflanzdichte. Der durchschnittliche Gesamtertrag an Biomasse und der kumulative Latexertrag pro Baum stieg in 40 Jahren um 28% bzw. 48%, wenn die Klimaszenarien vom Basisszenario bis zum höchsten CO_2-Emissionsszenario (RCP 8. 5) durchsimuliert wurden. Dieser Trend der Zunahme der Biomasse- und Latexausbeute mit verstärktem Klimawandel wurde auch auf der Ebene der Parzelle beobachtet. Dichtere Plantagen hatten eine größere Biomasse, aber die kumulative Latexproduktion ging drastisch zurück. Die während der Modellierung erstellten räumlich expliziten Output-Karten könnten helfen, die Kohlenstoffvorräte und die Latexproduktion regionaler Kautschukplantagen zu maximieren.

Allgemein ist für ein angemessenes Monitoring ein Kautschuk-basiertes System erforderlich, das sowohl in zeitlicher Hinsicht (Tages-, Monats- und Jahresebene) als auch in räumlicher Hinsicht (Pixel-, Landnutzungs-, Wassereinzugs- und Landschaftsebene) geeignet ist. Die Ergebnisse der vorliegenden Studie verdeutlichen die Bedeutung ökologischer Modellierungswerkzeuge im Naturressourcenmanagement. Die hier gemachten Erfahrungen könnten auch auf andere Kautschukanbaugebiete übertragen werden, indem sie mit standortspezifischen Umweltvariablen aktualisiert werden. Die bedeutende Rolle des Kautschukbaums ist nicht nur auf dieHerstellung von Naturlatex beschränkt, sondern liegt auch in seinem großen Potenzial zur Kohlenstoffbindung. Unsere Ergebnisse lieferen den Ausgangspunkt für die künftige Entwicklung umfassender Strategien zur Anpassung an den Klimawandel und zur Eindämmung des Klimawandels in Südostasien. Durch interdisziplinäre Zusammenarbeit könnte der nachhaltige Kautschukanbau in den Großen Mekong-Regionen realisiert werden.

Measuring and monitoring rubber plantations' carbon stock play significant role in regional and global carbon cycle. However, the existing models applied in rubber-based system are constrained by their application geographical scale, and the difficulty to transfer tree or stand level assessment into landscape level. Here the challenge mainly arises from the necessity of spatially explicit information to represent driving variables that have an impact on the landscape. This PhD thesis focuses on providing a comprehensive carbon stock assessment approach, by integrating process-based model, GIS technique and intensive field survey. The results are validated by regional stakeholder and will be used for guiding rubber management in marginal regions.

Bundesministerium für Bildung und Forschung
SURUMER
World Agroforestry Centre
Kunming Institute of Botany CAS
Universität Hohenheim