Holding Forests Accountable:

APFNet and Forest Carbon Accounting

Asia-Pacific Network for Sustainable Forest Management and Rehabilitation

China Forestry Publishing House

Holding Forests Accountable:

APFNet and Forest Carbon Accounting

Asia-Pacific Network for Sustainable Forest Management and Rehabilitation

China Forestry Publishing House

图书在版编目（ＣＩＰ）数据

亚太森林组织与森林碳计量 = Holding Forests Accountable: APFNet and Forest Carbon Accounting : 英文 / 亚太森林恢复与可持续管理组织组织编写 . -- 北京 : 中国林业出版社 , 2022.12

ISBN 978-7-5219-1999-8

Ⅰ . ①亚… Ⅱ . ①亚… Ⅲ . ①森林—二氧化碳—计量方法—英文 Ⅳ . ① S718.51

中国版本图书馆 CIP 数据核字 (2022) 第 235997 号

Data of Cataloguing In Publication

Holding Forests Accountable: APFNet and Forest Carbon Accounting / Asia-Pacific Network for Sustainable Forest Management and Rehabilitation. Beijing: China Forestry Publishing House, 2022.12

ISBN 978-7-5219-1999-8

Ⅰ . ① A… Ⅱ . ① A… Ⅲ . ① Forest — Carbon — Metering Method — English Ⅳ . ① S718.51

China CIP(2022)No.235997

Editors-in-charge: ZHENG Yuxin

First Published in the P. R. China in December 2022 by China Forestry Publishing House（No.7, Liuhaihutong, Xicheng District, Beijing 100009）E-mail: 377406220@qq.com　TEL：86-010-83143520

Printed and bound in by Jingping Chenqian Printing Limited Company, Hebei, China

Format：889mm × 1194mm 1/16

Printed sheets：6.25

Wordage：200,000

Price: CNY 68.00

PREFACE

The Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet) is dedicated to advancing sustainable forest management and forest rehabilitation in the Asia-Pacific region. With 32 members, including 27 economies and five international organizations, APFNet has helped its members promote sustainable forest management and forest rehabilitation via capacity building, demonstration projects, policy dialogues, and information sharing. One of APFNet's priorities is to enhance forest carbon stocks and improve forest quality and productivity by promoting the rehabilitation of existing but degraded forests and the reforestation and afforestation of suitable lands in this region.

Over the past four decades, forests have mitigated climate change by absorbing about one-quarter of the carbon emitted by human activities. As forests are a vital part of the global carbon cycle and help maintain Earth's carbon balance, accounting for carbon stock and emissions in forests is deemed important in the global effort of combating climate change. APFNet has contributed to these efforts by supporting project partners to develop new and improved methods to measure carbon on regional, national, and local scales and demonstrate how to enhance carbon storage via forest management. Specifically in this book, we include contextual information about MRV processes, carbon accounting methodologies, international reporting, and a full overview of APFNet's efforts in carbon emissions accounting and carbon stocks to help APFNet member economies gain insights into our work and improve the tools to enhance their efforts in carbon accounting.

Finally, I would like to say thank you to everybody involved in the compilation of this book. I hope it will serve to inform the international community's desire to further understand carbon accounting in the Asia-Pacific region.

Lu De
Executive Director
APFNet Secretariat

ABOUT APFNET

The Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet) is a non-profit international organization dedicated to advancing sustainable forest management and rehabilitation in the Asia-Pacific region.

In spite of an increasing awareness of the importance of managing forests sustainably toward achieving green growth, reducing poverty and responding to climate change, large gaps still exist in knowledge and capacities at global and regional levels. The establishment of the organization was proposed in this context by China and co-sponsored by Australia and the United States at the 15th APEC Economic Leaders' Meeting, in Sydney, Australia, in September 2007. The proposal was adopted by the APEC Leaders and incorporated in the Sydney Declaration on Climate Change, Energy Security and Clean Development, in an effort to "enhance capacity building and strengthen information sharing on sustainable forest management in the forestry sector" in the region.

The APFNet was officially launched in September 2008, with its arrangement and operations guided by the Operational Framework, evolved from the Framework Document jointly developed by China, Australia and the United States.

ACKNOWLEDGEMENTS

This book was written by Ms. Zhang Shiyi, Ms. Anna Finke, Mr. Li Zhaochen, Ms. Xin Shuyu and Mr. Li Zhi from the Project Management Division of APFNet's Secretariat. Ms. Julie Chua designed the book. We would also like to thank Dr. Lu De, the Executive Director of APFNet, who recommended the writing of this book and approved its final version.

The publication has also benefited immensely from the many people who contributed to APFNet's carbon-focused projects. This, in particular, applies to Dr. Wang Guosheng, from the Academy of Forestry and Grassland Inventory and Planning (China), Dr. Haruni Krisnawati from the Agency for Standardization of Environment and Forestry Instruments (Indonesia); Dr. Jiang Chunqian from the Research Institute of Forestry, Chinese Academy of Forestry; Dr. Khwanchai Duangsathaporn from the Kasetsart University Faculty of Forestry (KUFF) in Thailand; Dr. Pang Yong and Dr. Lei Xiangdong from the Institute of Forest Resource Information Techniques at the Chinese Academy of Forestry. Furthermore, several other people from our Executing Agencies (EAs) played a key role in providing the knowledge materials for this report. These people include Dr. Luba Volkova from the University of Melbourne (Australia), Mr. Li Xianze from Wanzhangshan Forest Farm (China), Mr. Ma Chenggong from Wangyedian Forest Farm (China), as well as other key project partners in the APFNet projects and made suggestions regarding this document.

Finally, our greatest acknowledgment goes to all the policymakers, researchers, professionals, and practitioners who contributed to the projects, without your efforts this book would not exist.

TABLE OF CONTENTS

TABLE OF FIGURES, BOXES AND TABLES

ACRONYMS AND ABBREVIATIONS

AFOLU	Agriculture, Forestry and Other Land Use
AGB	Aboveground Biomass
APEC	Asia-Pacific Economic Cooperation
APFNet	Asia-Pacific Network for Sustainable Forest Management and Rehabilitation
BCF	Biomass Conversion Factor
BEF	Biomass Expansion Factor
BURs	Biennial Update Reports
CAF	Chinese Academy of Forestry
CCER	Chinese Certified Emissions Reductions
CF	Combustion Factor
COP	Conference of Parties
CWD	Coarse Woody Debris
DBH	Diameter at Breast Height
DDF	Dry Dipterocarp Forest
DEF	Dry Evergreen Forest
DGPS	Differential Global Positioning System
ETF	Enhanced Transparency Framework
FAO	Food and Agriculture Organization
FD	Forest Department, Myanmar
FIPI	Forest Inventory & Planning Institute, Viet Nam
FLOU	Forestry and Other Land Use
FOERDIA	Forestry and Environment Research Development and Innovation Agency
FREL	Forest Reference Emissions Level
FRIM	Forest Research Institute Malaysia
GDANCP	General Directorate of Administration for Nature Conservation and Protection, Cambodia
GEF	Global Environmental Facility
GFIPI	Guangxi Forest Inventory & Planning Institute, China
GHG	Greenhouse Gas
GIS	Geographic Information System
GMS	Greater Mekong Subregion
GPS	Global Positioning System
GU	Guangxi University, China
HWP	Harvested Wood Products
IBP	International Biological Program
ICA	International Consultation and Analysis
IFRIT	Institute of Forest Resource Information Techniques
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IVI	Importance Value Index
KUFF	Kasetsart University Faculty of Forestry
LiDAR	Light Detection and Ranging
LULUCF	Land Use, Land-Use Change and Forestry
MDF	Mixed Deciduous Forest
MRV	Measurement, Reporting, and Verification
NAMA	Nationally Appropriate Mitigation Actions
NBS	National Bureau of Statistics
NDC	Nationally Determined Contributions
NDVI	Normalized Difference Vegetation Index
NIR	National Inventory Report
NTFP	Non-Timber Forest Product
NUL	National University of Laos
OLI	Operational Land Imager
PES	Payment for Ecosystem Services
PSF	Peat Swamp Forest
PyC	Pyrogenic Carbon
RADAR	Radio Detection and Ranging
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RFD	Royal Forest Department, Thailand
SAR	Synthetic Aperture Radar
SFM	Sustainable Forest Management
SFU	Southwest Forestry University, China
SOM	Soil Organic Matter
SRLCC	Special Report on Climate Change and Land
SVM	Support Vector Machine
TIRS	Thermal Infrared Sensor
TNC	The People's Republic of China Third National Communication on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
WYDFF	Wangyedian Forest Farm

EXECUTIVE SUMMARY

This publication was compiled in the face of the increasing threat posed by climate change to provide policymakers, practitioners, and other professionals with new insights into their carbon accounting. This book, while associated with the online seminar “Holding Forests Accountable – APFNet Forest Carbon Zoom Webinar” held on December 8, 2021, is a stand-alone knowledge product aiming to share APFNet’s research on carbon accounting methodology and experiences on forest carbon measurements.

The book is divided into several parts: Chapter 1 introduces the importance of carbon accounting and the context of the original webinar. Chapter 2 explains the most important frameworks relating to international reporting on carbon, the MRV system including an introduction on its history, how national carbon inventories are conducted, and which data are being reported in which frequency and institutions. As a large share of the projects covered in this report is located in China, China was also chosen as a case study to outline the MRV process in more detail, thus later benefiting the readers when learning about carbon accounting projects in the same economy. Chapter 3 gives an overview of the actual methodologies that can be used to implement forest carbon accounting on the ground for both small and large scales, while Chapter 4 presents APFNet’s overall goals and strategic directions in the space of carbon accounting, including the key areas APFNet has identified as priority work areas. Chapters 5-9 then introduce specific APFNet projects, starting with a project in Indonesia aiming to improve the accounting of carbon emissions from peatland fires (Chapter 5), followed by a project that developed new improved equations to estimate standing tree carbon for national reporting in Thailand (Chapter 6). Chapter 7 moves from pure methodology to a project that assessed carbon storage before and after restoration in the hilly mountains of Anhui and Zhejiang, China, while in Chapter 8, for the first time, the entire carbon stock of a forest farm in Inner Mongolia, China, was estimated purely via on-the-ground measurements. In Chapter 9, larger-scale methods using GIS, including LiDAR, are introduced in a project covering much of Southeast Asia. Finally, Chapter 10 summarizes the key ideas from different APFNet projects, followed by the conclusion of Chapter 11.

We hope that through this book our readers not only gain insights into APFNet’s work but also draw inspiration for how to improve on carbon accounting that he or she may be involved in.

With the amount of time to act on climate change shrinking every day, organizations cannot afford to be content with doing their projects. Knowledge ought to be shared. In this spirit, APFNet and the team of the Project Management Division hope you will find this book insightful.

Chapter 1

INTRODUCTION

BACKGROUND

Copious evidence has indicated that global climate change already led to environmental changes and influenced human social and economic activities and is likely to continue to do so. Unmitigated global emission of greenhouse gases (GHGs) may make the planet virtually uninhabitable for modern human society. As one of the largest terrestrial ecosystems, forests act as a stabilizing factor addressing to climate change by providing important habitat, supporting local livelihoods, and most importantly by regulating the carbon cycle. Forests can act as carbon sinks and store carbon in live trees, standing dead trees, fallen wood, the forest understory, and the soil. Carbon stored in these different components is continuously cycled among these pools and can be integrated into the forest long-term or re-emitted to the atmosphere.

Due to their complex relationships with carbon, forests' role in climate change is two-fold. On the one hand, forests act as an emission source of GHGs. Importantly, while forests always emit some emissions (e.g. through respiration and decomposition), they mostly act as a net emission source when disturbed, degraded, deforested or burned. According to the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Climate Change and Land* (SRCCL; 2019), the agriculture, forestry, and other land use (AFOLU) sector represents 23% of net anthropogenic emissions, while deforestation and forest degradation contribute to half of these emissions (IPCC, 2014). Additionally, the loss of forests also jeopardizes biodiversity and ecosystem functioning, thus decreasing their capacity to adapt to climate change themselves.

On the other hand, forests have the potential to combat global climate change by removing GHGs from the atmosphere or decreasing net emissions. Forests across the globe capture 2.6 billion tons of carbon dioxide annually (IUCN, 2021). One study found that forests and other ecosystems could provide more than one-third of the total CO_2 reductions required to keep global warming below 2 °C by 2030 (Griscom et al., 2017). In this context, national contributions and international cooperation can proactively mitigate climate change through adopting cost-effective approaches in the forestry sector, including combating deforestation and forest degradation, restoring forest landscapes, afforesting, practicing sustainable forest management, enabling rights-based land use, and advocating for sustainable forest benefits. For example, the global effort of the Bonn Challenge to restore 350 million hectares of degraded land by 2030 could sequester up to 1.7 Gt of carbon dioxide annually (IUCN 2021). Achieving the *Paris Agreement* could turn forests and other natural terrestrial ecosystems into a net sink by 2050.

However, there is no way of quantifying the contribution of these different actions and initiatives without measuring the carbon stored on site. Forest carbon accounting is thus a crucial component in the process of mitigating and adapting to climate change. The measurement of the baseline of forest carbon stocks and changes of carbon in various forest management scenarios enables forest stakeholders not only to gain knowledge on the current contributions their forests make to climate change mitigation, but also to understand the potential of those forests to sequester additional carbon over a given time period. On regional or national level, this information can be used to report on carbon sequestration from the forestry sector. Through this process, actions such as afforestation, sustainable forest management, and reducing deforestation and degradation can be transferred into calculable carbon credits, allowing trade in carbon markets that can benefit local stakeholders and enable forest carbon to be formally included in climate policy targets. These sets of data also provide critical basis to facilitate cooperation, guide further actions, and compensate behaviors that curb climate change.

The forest carbon accounting guidance from the IPCC is the primary source of guidance on forest carbon measurement. However, IPCC guidance is vast and challenging to navigate, and many forestry practitioners lack assistance to interpret the guide and select and apply a methodology suitable to their sites. Generally, their carbon accounting methodologies are still generic and not adapted to the local sites, potentially leading to large errors. Having a network support their endeavors to further best practices in carbon accounting and establishing a platform to communicate those concepts and methodologies would benefit both practitioners and the general public.

A NETWORK AND PLATFORM FOR FOREST CARBON ACCOUNTING

Recognizing the regional need for further support on forest carbon accounting, the APFNet has launched five different projects regarding this topic so far. These projects, situated in different locations in China, the Greater-Mekong Subregion (GMS), and Southeast Asia, measure carbon stocks and/or emissions through ground measurements or aerial images, selecting the most effective and efficient measures that are applicable to the respective economy and site conditions. While valuable data on forest carbon has been collected and analyzed, further communication between these practitioners and experts would allow them to exchange experiences, share lessons learned, and better understand international standardized carbon accounting methodology.

This book gives a comprehensive introduction to APFNet's carbon-related projects. Ultimately, the aim is to leave the readers with new insights on carbon accounting and good understanding of APFNet's involvement in this area of work.

Chapter 2

INTERNATIONAL REPORTING ON FOREST CARBON

THE MEASUREMENT, REPORTING AND VERIFICATION (MRV) SYSTEM

The United Nations Framework Convention on Climate Change (UNFCCC, hereinafter the Convention), which went into effect on March 21, 1994, set the foundation for the current system of collecting information on its implementation to prevent dangerous human interference with the climate system. Parties to the Convention are the 197 economies that have ratified the *Convention* (UNFCCC, 2021). The UNFCCC's ultimate goal is to prevent dangerous human involvement with the climate system. Information on GHG emissions by sources and removals by sinks, as well as activities taken by Parties to mitigate and adapt to climate change and implement the *Convention*, is critical in determining the *Convention*'s success at both the international and national level (UNFCCC, 2021). Parties to the UNFCCC are obligated to report to the Conference of the Parties (COP) about the activities they have taken or plan to take to implement the *Convention*. This is seen as a critical part of the *Convention*'s implementation since it allows Parties to share information about their national-level initiatives and serves as a foundation for the COP to assess the success of the agreed upon measures.

The Convention's reporting provisions were considerably reinforced through the *Bali Action Plan,* which was agreed upon at the COP 13 in 2007 (UNFCCC, 2014). In the context of strengthening action at the international and national level to combat climate change, the Bali Action Plan adopted the notion of measurement, reporting, and verification (MRV) for both developed and developing economies. Following a series of COP decisions, this idea was progressively further developed during 2004-2013, resulting in a full MRV framework under the Convention. The existing MRV framework includes submitting national communications every four years and biennial update reports (BURs) every two years (Figure 2.1), engaging in international consultation and analysis (ICA), establishing a domestic MRV of domestically supported nationally appropriate mitigation actions (NAMAs), which refer to mitigation actions by developing economies that aim at achieving a deviation in GHG emissions relative to 'business as usual' emissions in 2020, and conducting MRV of Reducing Emissions from Deforestation and Degradation (REDD+) activities for the purpose of obtaining and receiving results-based payments for ecosystem services (PES). The COP also addressed financial and technical assistance aimed at assisting poor nations in meeting their reporting obligations and improving the technical analysis of their BURs, which is one of the ICA process' phases (UNFCCC, 2014).

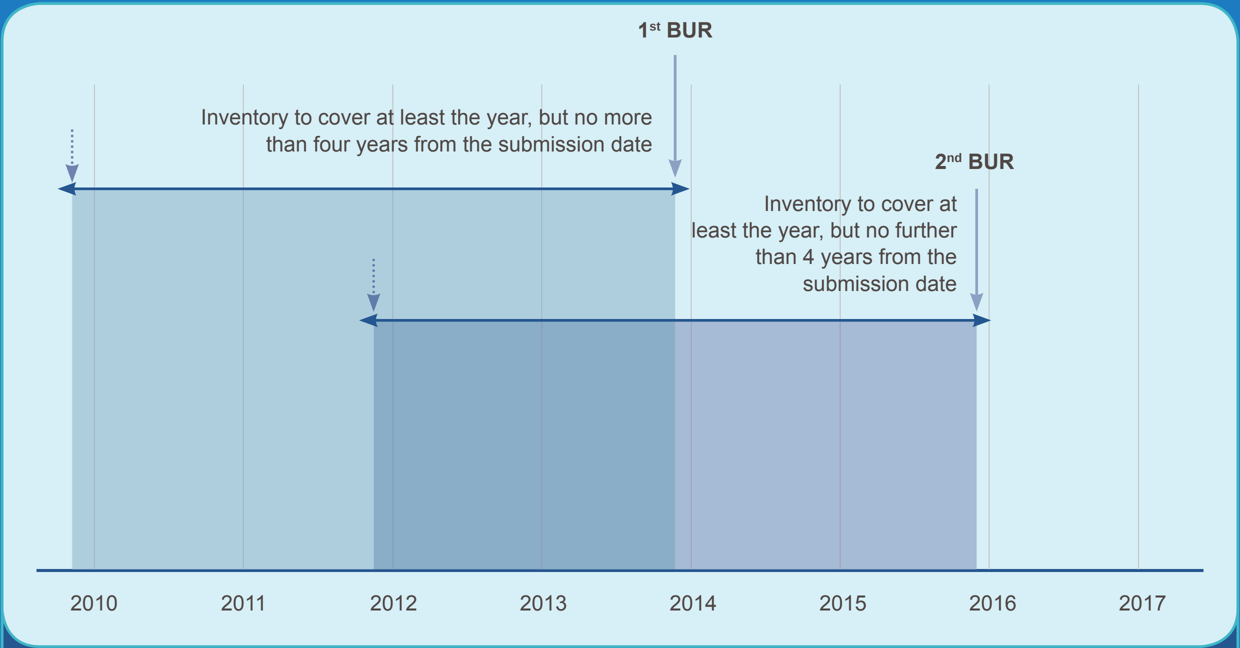


FIGURE 2.1: Example of years for which inventory should be reported for Parties submitting their first BUR in 2014 (UNFCCC, 2014)

The *Paris Agreement* brings all nations together in a common cause to make important measures to combat climate change and adapt to its impacts. In 2015, the Enhanced Transparency Framework (ETF) under the *Paris Agreement* was established to track, compare, and comprehend these national commitments. The ETF was established both for actions for post-2020 climate change commitments and nationally determined contributions (NDCs). Each economy will regularly submit a national inventory report (NIR) on emissions and removals, and materials to track progress of its NDC, as well as information on climate impacts and adaptation, and information on financial, technology transfer, and capacity-building support provided, needed, and received. National MRV systems establish and ensure reporting on a regular and continuous basis, while ETF is a central component for the credibility and operation of the *Paris Agreement* that will enhance the current MRV reporting requirements under the *Convention*. The better economies are meeting the MRV requirements, the more they will be in a position to meet requirements under the ETF.

This universal MRV system applies to all Parties and thus ensures transparency and allows trust-building and builds confidence that Parties contribute their share to the global effort. However, quantitative evaluation of the NDCs is often challenged by a lack of sufficient data and a lack of comprehensive information on definitions, assumptions and methods applied by each economy. The process of MRV, which started at the COP 13 in 2007, is a crucial pillar in promoting the convention and implementation of the *Paris Agreement*.

Elements of MRV agreed upon include:

- Enhancing reporting in national communications, including GHG inventories, mitigation actions and their effects, as well as support received;
- Submitting BURs every two years;
- Conducting ICAs of BURs that aim to increase the transparency of mitigation actions and their effects;
- Subjecting both domestically and internationally supported mitigation actions to domestic MRV.

KEY ELEMENTS OF THE MRV FRAMEWORK

The existing framework for MRV under the *Convention* consists of several elements. Some of these elements are implemented at the international level and others at the national level. At the international level, the MRV framework provides guidance on reporting through delivering national communications, BURs and ICA, and on setting up domestic MRV frameworks. At the domestic level, the MRV framework deliveries determine arrangements for domestic MRV of domestically supported (voluntary) actions and report on domestic MRV in the BUR. Parties are expected to implement the international guidelines for domestic MRV frameworks and to prepare and report information according to the guidance on reporting through national communications and BURs, including information on GHG emissions and removals by sinks, mitigation actions and their effects, and support needed and received.

The procedures of MRV start with **measurements**. The scope of the measurements includes the level of GHG emissions by sources and removals by sinks, emission reductions, and various co-benefits, among other things. This type of measurement takes place at the national level. It is used to refer to the measurement of GHG emissions by sources and removals by sinks via national GHG inventories, which are reported in national communications. Parties must measure the precise net effects of national mitigation initiatives, as well as the support requested and received, in accordance with the resolutions made at the COP 16 and 17, and offer this information, including a national inventory report, as part of their BURs (Figure 2.2). The *Convention* does not define measurement methodology. As a result, Parties rely on methodologies created by other parties, such as the Intergovernmental Panel on Climate Change (IPCC), which is an independent body that assesses the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change. The COP cooperates closely with the IPCC to ensure the Panel can respond to the need for objective scientific and technical advice. At minimum, the COP identifies and endorses the methodology that Parties should apply.

FIGURE 2.2: The GHG inventory cycle (UNFCCC, 2014)

The second step of MRV is **reporting,** which is implemented through national communications and BURs. Parties are required to report on their climate change actions in their national communications, which must include information on GHG inventories, adaptation, mitigation actions and their effects, constraints and gaps, support needed and received, and other information deemed relevant to the *Convention*'s goals (Table 2.1). National communications are due every four years. BURs are due every two years and provide an update on the information offered in national communications, including national GHG inventories, mitigation activities, constraints, and gaps, as well as requested and received support.

At the international level, verification is handled through the ICA of BURs, which is a procedure for increasing the transparency of mitigation efforts and their results. An ICA does not apply to national communications. At the national level, verification is carried out through domestic MRV processes using general guidelines issued at the COP 19 in 2013. In the BURs provisions for domestic verification, that are part of the domestic MRV system, must be recorded.

TABLE 2.1: Elements subjected to MRV under the current international framework (UNFCCC, 2014)

What is measured?	What is reported?	What is verified?
• GHG emissions and removals by sinks; • Emission reductions (or enhancement of removals by sinks) associated with mitigation actions compared to a baseline scenario; • Progress in achieving climate change mitigation and adaptation (i.e. GHG emission reductions or enhancement of sinks and reduction in vulnerability), achievement of sustainable development goals and co-benefits; • Support received (finance, technology and capacity building); • Progress on implementation of mitigation actions.	• Data on GHG emissions and removals by sinks (the inventory as part of the national communication and the inventory update report as part of the BUR); • Data on emission reductions (or enhancements of removals by sinks) associated with mitigation actions compared to a baseline scenario (BURs, national communications); • Progress with implementation of the mitigation actions (BURs, national communications); • Key assumptions and methodologies; • Sustainability objectives, coverage, institutional arrangements and activities (in the national communications and BURs); • Information on constraints and gaps, as well as support needed and received.	• All quantitative and qualitative information reported in the BUR, on national GHG emissions and removals, mitigation actions and their effects, and support needed and received; • Data may be verified through national MRV and through ICA, where appropriate.

Based on the *Paris Agreement* requirements for regular stocktaking and reporting, transparency and implementation on mitigation and adaptation activities, the MRV framework meets all four challenges, including improving national GHG reporting, technical assessment and independent review, assessing mitigation and adaptation options, and supporting implementation and management.

NATIONAL GHG INVENTORIES

Under the UNFCCC, all Parties have commitments to promote mitigation actions and to report sources and sinks of anthropogenic emissions, including those of the land use and forestry sector. National reports, including National Communications and National GHG Inventories, biannual reports, or biennial update reports are submitted for reporting. Guidance on how to estimate anthropogenic emissions and removals in the land-use sector is contained in the *1996 Revised Intergovernmental Panel on Climate Change* (IPCC) *Guidelines* and the *2006 IPCC Guidelines*, which have provided a technically methodological basis of national greenhouse gas inventories. To maintain the scientific validity of the 2006 IPCC Guidelines, the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* was adopted and accepted during the 49th Session of the IPCC in May 2019.

In the 2006 IPCC Guidelines, Land Use, Land-Use Change, and Forestry (LULUCF) and Agriculture are merged into a two-part volume referred to as AFOLU (Agriculture, Forestry and Other Land Use). Until now, LULUCF and AFOLU have been addressed separately.

(1) LULUCF POOLS

The *2006 IPCC Guidelines* use six land-use categories, including forest land, cropland, grassland, wetland, settlement, and other land (e.g. bare soil, rock, ice, etc.) for the purposes of estimating anthropogenic emissions and removals from land use, land-use change and forestry. For each of the six land-use categories, emissions and removals from the following pools are estimated:

- Living biomass (separate above- and below-ground values are required by the *Kyoto Protocol*)
- Dead organic matter (deadwood and litter)
- Soil organic carbon (mineral and organic)
- Wood products, such as timber used in construction or furniture, referred to as harvested wood products (HWP) are reported as an additional pool under LULUCF

(2) LULUCF VS. AFOLU

In addition to CO_2 emissions and removals from gains and losses linked with the LULUCF pools and the six land use categories, there are additional agricultural practices on farms (Figure 2.3), such as burning of crop residues, fertilizer application, rice cultivation, and emissions related to livestock (enteric fermentation and manure management), which produce emissions, mainly of methane (CH_4) and nitrous oxide (N_2O). Such emissions were included under "Agriculture" in the Revised *1996 IPCC Guidelines for National GHG Inventories and the IPCC Good Practice Guidance*, rather than LULUCF. The primary distinction between LULUCF and Agriculture (this refers to the non-CO_2 emissions related to agricultural practices, and not to CO_2 emissions or removals from croplands, which are included in LULUCF) is that in LULUCF removals and carbon storage (as well as emissions) are possible, whereas in Agriculture, only emissions are possible. LULUCF becomes more complicated as a result of this (Iversen et al., 2014). Reporting on land use under the UNFCCC (e.g. through national communications and the national GHG inventory) is comprehensive, in the sense that it encompasses all categories of land and pools. Agriculture (see Section 1.2) was treated in a separate module (Module 4) from Land-use Change and Forestry (Module 5) in the Revised 1996 Guidelines. However, the 2006 Guidelines integrate Agriculture and LULUCF into a single volume (Volume 4 of the Guidelines) called "Agriculture, Forests, and Other Land Use" or AFOLU.

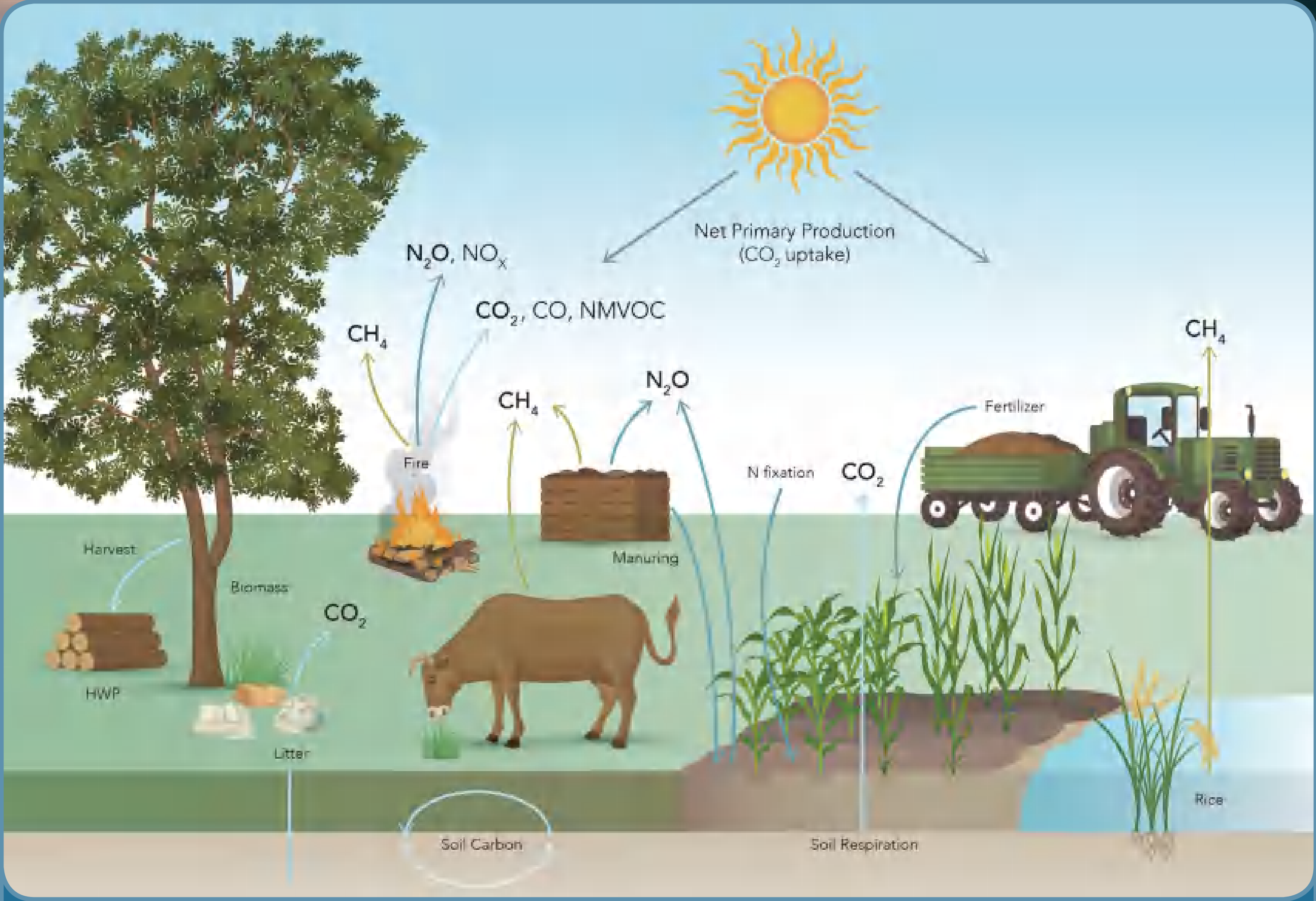


FIGURE 2.3: Land uses that result in emissions and removals (Iversen et al., 2014)

The IPCC Guidelines provide approaches, methodologies and technical guidance for preparing a GHG inventory for the LULUCF sector. The fundamental basis for the inventory methodology rests upon two linked assumptions:

I. The flux of CO_2 to/from the atmosphere is equal to changes in carbon stocks in the existing biomass and soils,
II. Changes in carbon stocks can be estimated by first establishing the rates of change in land use and the practice used to bring about the change (e.g. burning, clear-cutting, selective cutting, change in silviculture or management practice, etc.).

This requires the estimation of forest and land use in the inventory year, conversion of forest or grasslands, and the stocks of carbon in the above six land-use categories. The IPCC inventory methodology is categorized into tiers or levels. The more detailed the process and the more precise the emission estimations are, the higher the number denoting the tier. **Tier 1** is the most basic method, frequently utilizing IPCC-recommended economy-level defaults of deforestation rates, agricultural production statistics, and global land-cover maps. **Tier 2** is activity data defined by the economy for the most important land uses/activities. This level requires higher resolution data to correspond to specific regions and land-use categories. Generally, the use of a Tier 2 approach requires data on the amount of fuel combusted and an economy-specific emission factor for each gas, which is developed by taking into account economy-specific data, including carbon content of the fuels used, carbon oxidation factors, fuel quality etc. **Tier 3** is the most demanding in terms of complexity and data requirements. A Tier 3 approach divides the fuel combustion data into the following variables, with emission factors based on various combinations of each: statistics on the amount of fuel burned, an economy-specific emission factor for each gas, combustion technology, operating circumstances, control technology, maintenance quality, and the age of the fuel-burning equipment. It is preferable to utilize a national methodology consistent with the IPCC Guidelines, additionally it should be properly documented to justify why it is better than the default method proposed by the IPCC.

THE MRV PROCESS IN CHINA

Quantitative evaluation of the NDCs is challenged by the lack of sufficient data and comprehensive information on the definitions, assumptions and methods applied by each economy. To illustrate this, the MRV process in China is taken as a case study.

According to the *Paris Agreement* rules, from 2014 every party will submit a biannual national report, including an annual NIR using the *IPCC 2006 Guidelines* and information to track the implementation of the NDCs. Upon receiving grants from the Global Environment Facility (GEF) in 2015, the Chinese government launched the preparation of its first and second BUR and third national communication. The *People's Republic of China's Second BUR on Climate Change* was finished after more than three years of work. The duties of combating climate change were transferred from the National Development and Reform Commission to the newly founded Ministry of Ecology and Environment in 2018, as part of the Chinese government's institutional reform. After many revisions based on feedback from the State Council, the State Council then authorized this report, which was presented by the Ministry of Ecology and Environment together with the People's Republic of China's *Third National Communication on Climate Change* (TNC).

China only reported its National Greenhouse Gas Inventory in 1994, 2005, 2012, and 2014, after submitting two versions of the National Communication on Climate Change Report and two versions of the BURs (UNFCCC, 2018). The need of adopting yearly NIRs is demonstrated by the lack of consistency in GHG reporting and calculating of GHG in past years (Chen et al., 2021). China implemented several improvements in the second BUR to minimize uncertainties and enhance inventory quality, bringing its reporting standard closer to the IPCC Guidelines' NIR reporting framework. The National Bureau of Statistics (NBS) of China has created a statistical reporting system which reveals sector-specific emission factors and allows for more types of energy statistics to be reported. The inventory researched the rate of carbon storage in the coal and chemical industry, conducted an on-site measurement of nitrogen excretion by primary livestock and poultry, and analyzed direct emission factors of N_2O from agricultural soils. Given the accuracy of China's BUR, it is feasible for China to apply the existing data reporting system in NIR reporting (Chen et al., 2021).

The second BUR is divided into six parts: ① National Circumstances and Institutional Arrangements, ② National Greenhouse Gas Inventories, ③ Mitigation Actions and their Effects, ④ Funds, Technology and Capacity-Building Needs and Support Received, ⑤ Basic Information of the Hong Kong Special Administrative Region on Addressing Climate Change, ⑥ Basic Information of the Macao Special Administrative Region on Addressing Climate Change. Forest land, cropland, grassland, wetlands, settlements, and other land are all included in NGI 2014's land use, land-use changes, and forestry (LULUCF) category, which includes GHG

emissions and carbon sinks from six different land-use categories. Carbon stock change is computed for each kind of land use and land use change using estimates of the five carbon pools: aboveground biomass, belowground biomass, litter, dead wood, and soil organic matter (UNFCCC, 2018). The changes in soil organic carbon stores were calculated using a Tier 3 technique. In the *IPCC Good Practice Guidance for Forests*, the Tier 2 approach is used to evaluate changes in aboveground biomass, subsurface biomass, litter and dead wood, and soil organic matter (SOM) in other carbon pools. Wetland CH_4 was estimated using a Tier 1 method. In 2014, China's LULUCF absorbed 1,151 Mt CO_2, emitted 1.72 Mt CH_4, and the net removal of GHG amounted to 1,115 Mt CO_2 equivalent. Forest land, agricultural soils, grassland and wetland respectively absorbed 840, 49, 109 and 45 Mt of CO_2; settlements emitted 2.53 Mt of CO_2; harvested wood products absorbed 111 Mt CO_2. The CH_4 emissions from the wetland were 1.72 Mt.

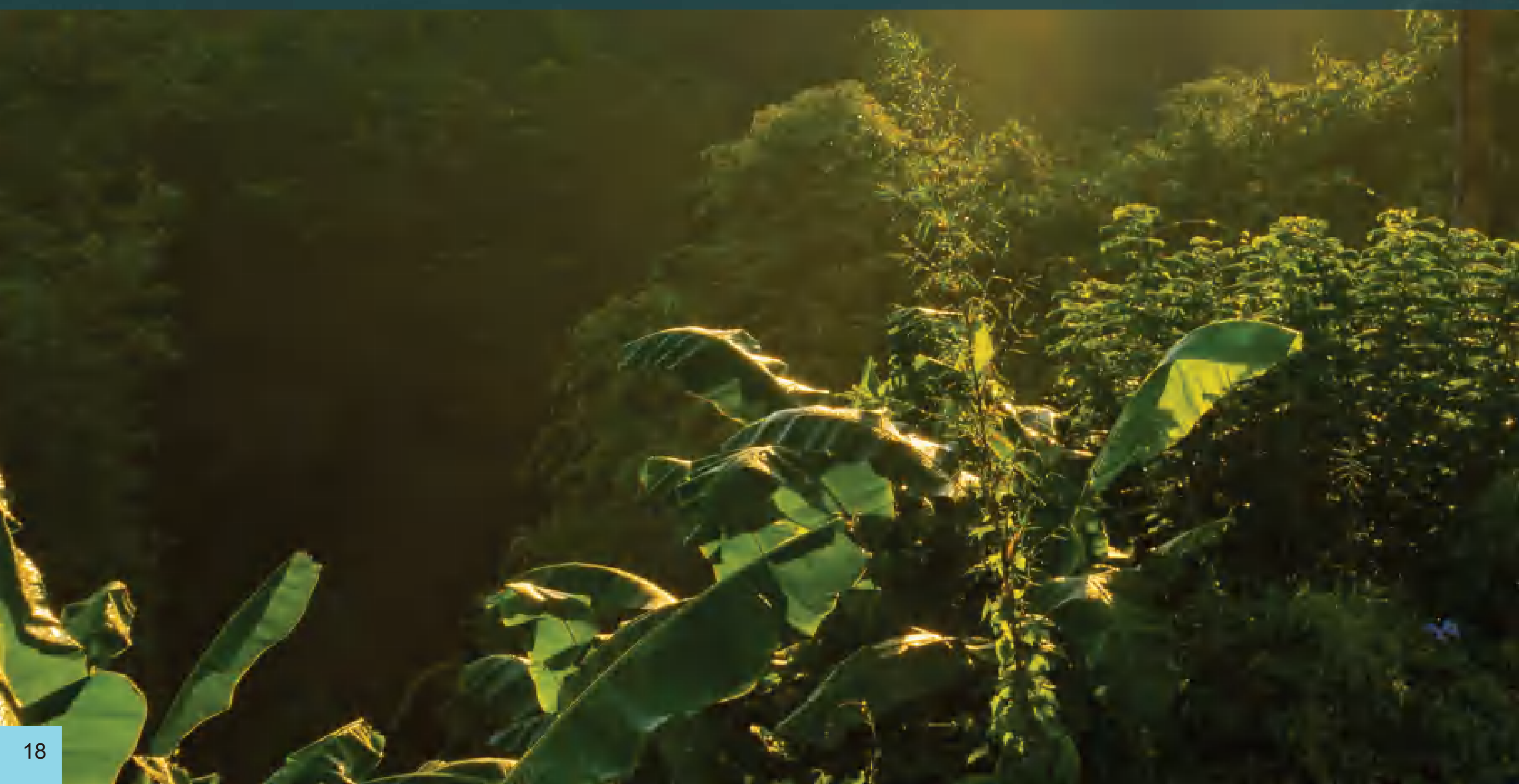
China meets the challenges of inventory and survey data of LULUCF every year for the annual NIR, improving accuracy of NIR of LULUCF results, inventories and surveys of forest projects using more concise modelling and Tier 3 data for estimation of carbon sinks/emissions on project level and for Chinese Certified Emissions Reductions (CCER) in the carbon market. All in all, the main problem for China is the time to submit the NIR (Table 2.2). As required the NIR has to be produced every year, but for grassland, there is no big change in grassland soil data.

TABLE 2.2: Timeline of MRV in China (UNFCCC, 2018)

Report	NIR	Guideline	Forest and land use	Tier
Initial National Communication	1994	IPCC 1996	FLOU	Tier 2
Second National Communication	2005	IPCC 1996 IPCC 2006 (some)	FLOU	Tier 2
Third National Communication	2010	IPCC LULUCF best practices	LULUCF	Tier 2
First BUR	2012	IPCC LULUCF best practices	FLOU	Tier 2
Second BUR	2014	IPCC 2006	LULUCF	Tier 2

Chapter 3

METHODOLOGIES



TIER-RELATED DIFFERENCES IN METHODOLOGY

As mentioned in Chapter 2, the IPCC guidance uses Tier structure and land representation. Economies choose from Tier 1, 2, and 3 approaches to calculate emissions and removals. While the IPCC methodologies established a model for measurement, choosing approaches from various tiers could alter the result of carbon accounting significantly in deforestation, forest degradation, reforestation, and forest management scenarios (Bird et al., 2010). In general, these methodologies vary in the selection of primary data, secondary data, and remote sensing-derived data. The lowest tier applies existing national, regional, or global data, default parameters and simplified methodologies for the estimation of GHG emissions and removals, but higher tiers require data collected in a longer term, higher resolution and adapted to local conditions. Tier 3 even requires models and inventory specific to address national circumstances. While the selection of secondary data reduces both time and cost for accounting, it does not provide as precise results as choosing primary data. In general, the IPCC suggests using a methodology for carbon source and sink that adopts region-specific and high-resolution data for reducing overall inventory uncertainty. However, these methods typically require more extensive resources for data collection, so not every economy is able to adopt the same method for every land use category. By assessing the available resources and identifying key objectives, an economy can prioritize its efforts and improve its overall estimates. It's also important to realize that the IPCC methodologies were specifically designed to calculate emissions and removals from land use and land use changes for national inventory, but they tend to provide less precise results when applied to project-based inventories. When estimating the carbon source and sink of a specific project, it is necessary to develop a tailored methodology to improve the accuracy of the estimation.

In general, which aims, scale, and forest management activities to include, and which carbon pools to account for, are some factors to consider when choosing forest carbon accounting models. As these models vary in the number and detail of input parameters, the outputs and their precision vary as well. Thus, no model can be considered as a universal standard. When an economy develops a forest accounting model for its NIRs or BURs, the model is only applicable to the forests in that economy.

DETERMINING THE FOREST ACCOUNTING TYPE

There are three types of forest carbon accounting: ① carbon stock accounting, ② carbon emissions accounting, ③ project carbon emission reductions accounting (Watson et al., 2009). This book emphasizes on carbon stock accounting and carbon emissions accounting as existing APFNet projects mainly focus on these two types. As such, the project carbons emissions reductions accounting will not be covered in detail in this chapter.

CARBON STOCK ACCOUNTING

Forest carbon stock accounting estimates the amount of carbon accumulated in carbon pools of a selected forested landscape at a single point in time. International standards typically recognize five carbon pools, including above ground biomass, belowground biomass, dead wood, litter, and soil carbon. Forests across the world store approximately 861 Gt of carbon, with 42% in live biomass (above- and belowground), 44% in soil, 8% in deadwood, and 5% in litter (Pan et al. 2011). Decisions on which carbon pools should be included are largely dependent on the availability of existing data, cost of data acquisition (inventory), and the level of precision desired.

There are several fundamental methods of vegetation carbon storage estimation, which can be subdivided into three basic types based on the data they are using for conducting the estimation: ① inventory-based estimation, ② satellite-based estimation, ③ carbon flux-based estimation.

(1) INVENTORY-BASED BIOMASS ESTIMATION

Inventory-based estimation of forest vegetation carbon stocks is a group of classical methods to quantify carbon stored within forest ecosystems (Fang et al., 2001; Shao et al., 2017). These methods are applied based on forest inventory data, such as forest types, stand age, stand density, stand volume, mean tree height and diameter at breast height (DBH; Tang et al., 2018). While estimating forest carbon stocks, most scholars assumed that carbon content in plant biomass is constant (approximately 50%; S. Brown, 1997; Matthews, 1993). Therefore, the methods used for estimating forest vegetation carbon stocks are almost entirely consistent with the ones used for biomass estimation, even though as the case study in Chapter 6 shows, carbon content within different species can vary significantly. It's also worth noting that these methods used to estimate forest biomass and carbon stocks vary depending on scale (from individual trees to stand level forests to regional level; Shi et al., 2017). In the past decades, allometric equations, the mean biomass method, or volume-derived methods (e.g., biomass regression equations and the conversion factor continuous method) were the most commonly used methods for estimating vegetation carbon storage based on inventory data (Table 3.1).

TABLE 3.1: Four commonly used methods for estimating vegetation carbon storage based on inventory data (Shao et al., 2017)

Methods	Scale	Basic formula
Allometric/biomass regression equation	Individual and stand levels	$M = a \times D^b \times d$ $M = a \times D^b \times H^C \times d$
Mean biomass density method	Stand and regional levels	$M = A \times m \times d$
Volume-derived method IPCC (Biomass Conversion and Expansion Factor)	Regional level	$M = A \times [V \times BCEF_s] \times (1 + R) \times d$
Volume-derived method Conversion factor continuous method	Regional level	$M = A \times V \times BEF \times d$ $BEF = a + \frac{b}{V}$

Note: M is the carbon storage; m is mean biomass density; A is forest area; d is the carbon content ratio of tree biomass, D is diameter at breast height; H is tree height; V is merchantable volume; BCEF is the biomass conversion and expansion factor applicable to growing stock which transforms merchantable volume of growing stock into above-ground biomass; R is the root-to-shoot ratio (the proportion of belowground biomass to aboveground biomass); BEF is the biomass expansion factor; a, b and c are constants changed along with forest type, species and climate zones.

Many studies used inventory-based biomass estimation methods to assess carbon stored for various scales in China. The four aforementioned methods have their own unique advantages and disadvantages, and there is no one-size-fits-all solution, meaning none of these methods mentioned work best on all levels from individual to large scale. The allometric equations are usually fitted (derived) by sampling biomass and D (and/or H) based on destructive sampling, and the developed equation can be applied to estimate individual-level and stand level biomass of standing trees (see Chapter 6). The mean biomass density method was widely used in estimating forest biomass on stand and regional scale before and during the *International Biological Program Period* (IBP was an effort between 1964 to 1974 to coordinate large-scale ecological and environmental studies), where one can estimate biomass for a stand or forest via the mean biomass density (that is through measuring the biomass in sample plots, then convert it to the mean biomass in an unit area) multiplied by the area (Whittaker, 1963). It was found that the mean biomass density method could easily lead to an overestimation due to the biased selection of sample plots, however, the accuracy could be improved through adding randomly selected sample plots in the study region (Shi et al., 2017). The most representative volume-derived biomass estimation method is the biomass expansion factor (BEF) method, which was later updated to the Biomass Conversion and Expansion Factor (BCEF) method provided by IPCC, which has been widely used to estimate vegetation biomass at larger scale. The method assumed there is a certain relationship between merchantable volume and aboveground tree biomass, thus, biomass can be estimated based on the merchantable volume multiplied by the BEF or BCEF conversion factor. Actually, BEF/BCEF varies a lot depending on forest age, site class, and stand density. Therefore, the BEF/BCEF method usually causes a relatively large deviation in middle and small scale estimations since the parameters provided are primarily for large scale estimations (Zeng et al., 2018). Fang et al (2001) argues that the variation of the BEF value can be expressed as a function of timber volume, which is expressed as $BEF = a + b/V$, to obtain a variable BEF value for each forest type. This method is called the Conversion Factor Continuous Method, which is now commonly used to estimate tree biomass.

(2) SATELLITE-BASED ESTIMATION

With the development and application of modern technologies such as Remote Sensing, the Geographic Information System (GIS) and the Global Positioning System (GPS), multi-source remote sensing data has become an alternative (and often less costly) means of quantifying forest AGB/carbon storage. At present, there are three main types of datasets used for estimating vegetation carbon storage: optical remote sensing, synthetic aperture radar satellite data (SAR), and Lidar data (LiDAR). The main principle for satellite-based carbon estimation is to construct relationships between satellite frequency band combination from the above-mentioned data and forest stand volume.

Optical remote sensing is a passive technique for earth observation relying on solar illumination. It makes use of visible, near-infrared and short-wave infrared sensors to form images of the earth's surface as different materials reflect and absorb differently at different wavelengths and can subsequently be differentiated by their spectral reflectance signatures. It has been widely used in studies to link aboveground biomass (AGB) measurements from the field to satellite observations. Optical remote sensing is extremely intuitive and sensitive, but the limitations, such as limited wavelength range, its inability to penetrate the forest canopy, obstruction by clouds or interaction with leaves, can affect the results.

SAR provides high-resolution remote sensing and is a form of radar used to create two-dimensional images or three-dimensional reconstructions of objects, such as landscapes. To create a SAR image, successive pulses of radio waves are transmitted to illuminate a target scene and the echo of each pulse is received and recorded. It is usually mounted on a moving platform, usually on a spacecraft and can provide resolutions of about 10cm. It has great advantages in estimating forest biomass and carbon storage due to its all-day, weather-insensitive imaging technology as it can see through clouds. Since the 1960's, SAR has been used to produce images of earth-surface features based on the principles of radio detection and ranging (RADAR, often used as a synonym for SAR) and has been widely used to map AGB.

LiDAR is an active ranging technology, meaning it's a method for determining ranges of variable distance by targeting an object or surface with a laser and measuring the time for the reflected light to return to the receiver. Through this method it has the ability to efficiently measure three-dimensional structures, enabling it to estimate the height and spatial structure of trees. LiDAR has been applied in the field of forestry, such as forest mensuration, forest fire management, forest mapping, land classification and other practices by attaching a LiDAR device on a satellite, an airplane, a backpack, or other vehicles. It is extremely high in resolution (more than SAR), but can be blocked by cloud cover. Research has indicated that this technology could improve the estimation accuracy of forest height and structure and forest carbon storage (Gwenzi et al., 2014).

(3) CARBON FLUX-BASED ESTIMATION

Flux-based carbon accounting directly measures the flow of carbon into and out of the forest. State-of-the-art sensors use a technique called *eddy correlation* to continuously monitor carbon exchange between all the carbon pools in a forest ecosystem and the atmosphere. Flux-based calculations are ideal for delivering information on short-term variations in the magnitude of the carbon sink and in quantifying net carbon exchange in forest systems, where the individual carbon pools are difficult to measure.

CARBON EMISSIONS ACCOUNTING

Carbon emissions accounting quantifies the exchange of GHGs between atmosphere, terrestrial vegetation and soils. Natural processes, such as fires, insects, typhoon, and human interactions, such as swidden agriculture, burning, and harvesting can lead to the emissions and removals of GHGs. Most emissions from forests come from deforestation and degradation. Generally, accounting for carbon emissions from deforestation tends to be easier to calculate, while forest degradation emissions highly depend on the type and level of degradation, as well as feedback loops within the forest. In fact, when it comes to reporting for payments for ecosystem services (PES), such as REDD+, most economies focus on reporting emissions from deforestation, generally estimating emissions based on carbon stocks per unit area and the area of land changing from forest to non-forest (FAO, 2019).

There are two approaches to account for emissions: the inventory approach and the activity-based approach (Watson et al., 2009). The inventory approach measures the difference in carbon stocks averaged between two points in time. One issue with reporting using the inventory approach is that, especially in developing economies, critical carbon pools that are more difficult to quantify, such as dead wood, soil or litter, are often not reported at all, meaning that the uncertainty stemming from emissions from these pools may be quite high (Yanai et al., 2020).

In contrast, the activity-based approach begins by identifying the activities for releasing or sequestering carbon and estimating the carbon consequences of those activities. This approach requires a good understanding of the rates of carbon gains (e.g. biomass growth) and losses and has to develop emission factors for biomass losses. An advantage of this approach is that some aspects, such as select logging or burning of an amount of biomass, may be more easily and quickly directly calculated than the entire carbon stock of a forest at different points in time. However, these calculations run the risk of not including feedback loop-based emissions, such as a carbon loss in soil induced by selective logging, as it increases the amount of sunlight hitting the ground.

The decision between these approaches depends on the availability of data and the objectives of the accounting. For example, the project in Chapter 5 used an inventory approach of carbon stocks at different points in time to eventually be able to provide calculation methods for an activity-based approach, specifically to estimate how much carbon in average is burned during a specific type of peat fire.

Equations of the two approaches for carbon emissions accounting:

① Inventory/Periodic Accounting:

$$\Delta C = \sum (C_{t2} - C_{t1})/(t_2 - t_1) \quad (3.1)$$

ΔC	Carbon stock change, tonnes C per year
C_{t1}	Carbon stock at time t_1, tonnes C
C_{t2}	Carbon stock at time t_2, tonnes C

② Activity-based/Flux Accounting:

$$\Delta C = \sum [A \cdot (C_I - C_L)] \quad (3.2)$$

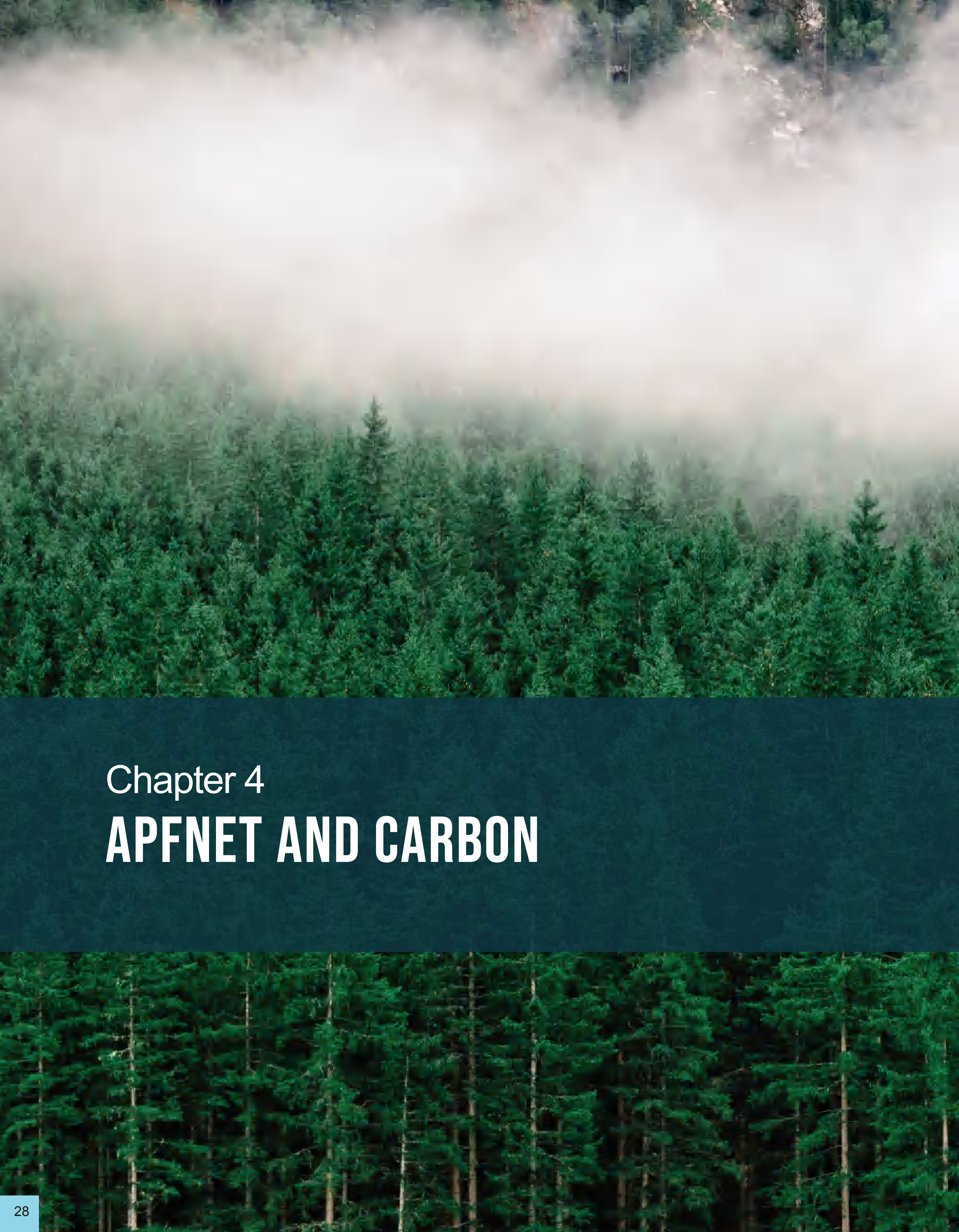
A	Area of land, hm^2
C_I	Rate of gain of carbon, tonnes C per ha per year
C_L	Rate of loss of carbon, tonnes C per ha per year

Source: IPCC (2003) as reflected in *Forest Carbon Accounting: Overview and Principles* (Watson, 2009)

As can be seen from this description, the measurement of carbon emissions is tightly correlated to the measurement of carbon stocks themselves. Without good data of the carbon stocks in a given piece of land, it is difficult to calculate carbon emissions of forests.

PROJECT CARBON EMISSIONS REDUCTIONS ACCOUNTING

Project carbon emissions reductions accounting is often applied when a forest carbon project reduces emissions and generates carbon credits to be traded under the *Kyoto Protocol* or on one of the voluntary carbon markets. This approach emphasizes on the importance of developing a baseline scenario which would have happened if the project or policy were not to exist. The mitigation impacts, such as reducing emissions from deforestation and degradation, can then be quantified by comparing it with the baseline.



Chapter 4

APFNET AND CARBON

The relationship between APFNet, climate change and carbon goes right back to its roots.

In 2007, APEC members jointly stated in the *Sydney Declaration* that “Economic growth, energy security and climate change are fundamental and interlinked challenges for the APEC region”, indicating their strong commitment to mitigating climate change (APEC, 2007). Subsequently, during the same APEC Ministerial Meeting the members then pledged to take four actions on climate change: ① setting an APEC-wide regional aspirational goal of a reduction in energy intensity by at least 25% by 2030 (compared to 2005); ② increasing forest cover by at least 20 million ha of all types of forest by 2020; ③ strengthening collaboration on energy research through the establishment of a dedicated network; ④ based on the proposal by China and in cooperation with Australia and the United States, establishing a new organization to promote sustainable forest management (SFM) and forest rehabilitation, while decreasing forest degradation in the Asia-Pacific region (APEC, 2007). This organization, of course, was the Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet), which was officially launched in 2008. While the aforementioned priorities are not solely connected to climate change, they certainly play a key role in increasing the carbon sink potential of forests and preventing emissions from forests through preventing deforestation and degradation.

Initial projects focused more strongly on implementing activities that will contribute in such a way, but later on the importance of carbon accounting became increasingly clear. This was in step with international commitments and goals by different APFNet member economies. For instance, Thailand’s formal Nationally Determined Contribution (NDC) aims to reduce GHG emissions by 30% by 2030 (UNFCCC, 2020). This is, however, a highly emissions-based target. Indonesia, while originally submitting a similarly structured target, now in its latest NDC submission to reduce GHG emissions by 29% by 2030, not only focuses on emissions from forests through e.g. forests fires, but also focuses on using reduced forest degradation and active restoration programs to increase total forest carbon sinks (Indonesia, 2016). China, meanwhile, sets its important goal of achieving total carbon neutrality by 2060 (UN News, 2021). These shifts, overall, send an increasingly strong signal that it is not just about carbon emissions but the total balance and with this, measuring a wider range of forest-related carbon is moving into focus.

Recognizing this trend, APFNet identified the enhancement of carbon stocks as one of its key objectives in its Strategic Plan 2021–2025 and determined a number of thematic areas and subsequent demonstration projects covering a large part of relevant forest-carbon issues, including: ① forest-based emissions, ② forest carbon storage potential, ③ on-the-ground carbon stock measurements, ④ GIS-based carbon mapping, ⑤ developing measurement methods and procuring data for local, regional, national and international use and reporting.

(1) FOREST-BASED EMISSIONS

This is, as earlier mentioned, the most traditional role forests have played in national reporting, by reporting emissions from deforestation and degradation. As such, APFNet primarily supports efforts to determine forest-based emissions in more niche areas. One such area is emissions from peatland fires, which are often based on rather crude calculations, assuming full combustion at the first fire. The project in Chapter 5 covers this issue, developing a better way to measure those emissions.

(2) FOREST CARBON STORAGE POTENTIAL

Mechanisms like REDD+ are based on the idea that wood, that is not harvested but left standing to store carbon, also has value. Determining the maximum storage capacity that a forest can have under sustainable forest management thus gives a local community, a company or even a nation the tools to determine their climate mitigation potential and adds support for restoration efforts. In the case of the APFNet-supported projects at Wanzhangshan and Wangyedian Forest Farm (Chapter 8), both current and future potential forest carbon stocks for the entire farm are calculated to improve SFM methods and align the farm's long-term strategic forest management with China's aforementioned carbon neutrality goal.

(3) ON-THE-GROUND FOREST CARBON STOCK MEASUREMENTS

When existing carbon stocks in forests are quantitatively measured, forest ecosystem services beyond timber are put into the foreground and can be formally included in Payments for Ecosystem Services (PES) schemes, including carbon markets. Especially in poor communities with stricter rules on logging, being able to obtain additional income through PES beyond NTFP profits may push livelihoods from subsistence or low income to middle income and beyond. One APFNet project (Chapter 6) focused on measuring carbon stocks on different sites after restoration measures of silvicultural treatments were implemented, illustrating how sustainable forest management and carbon stocks can increase through these measures while also providing other ecosystem services.

(4) GIS-BASED CARBON MAPPING

Measuring everything from the ground up can prove to be unfeasible for larger-scale carbon mapping. As such, the GIS-based carbon inventory proves to be an invaluable tool to generate such data. In particular, Lidar is a useful tool in this context. In one APFNet project (Chapter 9) the goal was thus to use Lidar to estimate forest biomass and subsequently forest carbon stocks. Combined with field measurements and other data for ground-truthing, larger, regional areas can be estimated.

(5) LOCAL, REGIONAL, NATIONAL AND INTERNATIONAL USE AND REPORTING

Information on carbon, while by itself useful to have, only truly incites change when integrated into formal reporting and measurement mechanisms. As such, a number of APFNet projects, such as a project in Thailand attempting to develop better standing tree carbon calculation methods (Chapter 6), aim to use the developed methods to improve their formal reporting, such as their NDC reporting to the UNFCCC.

Moving forward APFNet aims to continue to support partners and ideas that relate to the identified key issues above. APFNet carbon projects are envisioned to supply partners, members and other professionals with a better understanding of the potential of “green carbon capture” from local to national, regional, and international scale, improve their reporting to official bodies related to climate change, help them align their long-term strategic forest planning to international climate goals, integrate the overall concept of multifunctional forestry with specific carbon goals, and overall change the perception of the role that carbon plays in forestry.

Chapter 5

NOT ALL EMISSIONS ARE CREATED EQUAL: FILLING KNOWLEDGE GAPS REGARDING PEATLAND FIRE EMISSIONS

Project title: Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia [Project ID: 2018P5-IND]

Supervisory agency: Ministry of Environment and Forestry

Executing agency: Forest Research and Development Center, Forestry and Environment Research Development and Innovation Agency (FOERDIA)

Total budget (USD): 498,170

APFNet grant (USD): 199,990

Start date and duration: January 2019, 01/2019 – 12/2021 (extended until 03/2022)

Target economy: Indonesia

Site location: Kalimantan, Indonesia

Contacts: Project coordinator: Dr. Haruni Krisnawati (h.krisnawati@yahoo.co.id)
University of melbourne: Dr. Luba Volkova (lubav@unimelb.edu.au)

EXPECTED OUTPUTS/OUTCOMES:

- Improved estimates of GHG emissions (CO_2 and non-CO_2) from peat swamp forest fires based on comprehensive field measurements;
- An updated methodology on estimating GHG emissions from PSFs for Indonesia's international reporting;
- A set of recommendations for reducing GHG emissions from forest fires;
- High quality peer-reviewed publications making results of the project transparent and readily available for international reporting and verification under the UNFCCC requirements for the result-based payments on emission reduction.

KEY ACTIVITIES:

- Comprehensive literature review, development of a statistically robust experimental design and the baseline of emissions from PSF fires measurement of fuel loads and pyrogenic carbon in the field;
- Data analysis of the relationship between fire intensity and fuel consumption and emission release;
- Development of policy recommendations for GHG emission reduction in PSFs based on the results of the field study.

FIGURE 5.1: The project team on the way to the tropical peatlands
Photo: Anna Finke/APFNet

INTRODUCTION

As already explained in Chapter 2, the process of MRV includes GHG inventories, which was already in its basic tenets agreed upon in Article 3.4 of the *Kyoto Protocol* (UNFCCC, 1998), of which both carbon sinks and sources are recorded. While forests are commonly understood as a carbon sink, they can become carbon sources through specific disturbances, such as land conversion or burning. Reports for LULUCF emissions are to be delivered annually via NIRs. All emissions are accounted for towards a reference level, usually comparing it to a business-as-usual-projection, as a net-net accounting approach and can exclude emissions resulting from natural disturbances (Krug, 2018). Importantly, that does not include human-induced natural disturbances, such as purposely set forest fires (Figure 5.1).

A landscape that has significant influence on source or sink effects of forests are tropical peatlands. As areas with high carbon density, they cover about 36.9 million ha across Asia. Indonesia has the largest share of peatlands with a total of 20.7 million ha (Leng et al., 2019) and the largest share of tropical peat carbon (Page et al., 2011). This large carbon storage area is threatened, however, by land conversion. Peatland drainage for agriculture and plantations is often followed by burning to remove remaining vegetation, releasing large amounts of GHG emissions in the process. As such, accurately estimating these emissions is of great importance to mitigate climate change, and has been determined by FAO as a global strategic priority (FAO, 2012).

However, as remarked upon in Chapter 2 and 3, many economies still rely on the generic Tier 1 calculation methods provided by the IPCC (Eg-gleston et al., 2006)[a]. The default combustion factor (CF) parameters of these methods assume that a singular fire releases 100% of the carbon in peat and 50% of aboveground carbon. This, however, is unlikely to be the case as peat fires are generally dominated by smoldering combustion, a flameless form of burning. Opposed to normal fires, smoldering fires can persist under low temperatures, in moist conditions and with almost no oxygen. As a result they can burn for weeks or months despite rain or changes in fire weather. When the fires do extinguish, without an extensive body of baseline data identifying patterns in burning behavior, it is hard to say how much of the peatland has burned and how much carbon has been emitted. Factors, such as fuels loads (including fuel types), area burned (including severity and patchiness of the burn), the CF and emission factor (both determined by the fuel type) ultimately determine how many GHG emissions are released in a given burn. Additionally, the standard IPCC parameters themselves are only based on a small number of studies, thus improvements in calculating methods may

[a] *A refinement of these calculation methods has been posted under the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, but this was before project start and thus would not reflect the conditions under which the project was started.*

For an economy like Indonesia, where emissions from LULUCF are amongst the highest contributions to their overall national emissions, inaccurate estimates from peat fires can be highly detrimental. As such, when it sets its Nationally Determined Contribution (NDC) to reduce emissions by 29% relative to a business-as-usual scenario by 2030 (Indonesia, 2016), emissions from peat fires were excluded from its first Forest Reference Emission Level (FREL) submitted to the UNFCCC and are to date not included in official reporting (MoEF, 2016). This, however, prevents it from subsequently claiming emission reductions from reduced peat fires as well. Clearly, an improved calculation methodology was needed.

In 2019, APFNet funded the project "*Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia*", which is executed by an international collaboration between Indonesia's Forest Research and Development Center at the Forestry and Environment Research Development and Innovation Agency (FOERDIA), which in the beginning of 2022 was renamed to the *Agency for Standardization of Environment and Forestry Instruments*, and the University of Melbourne in Australia. The chief goal of this project is to provide the lacking empirical data on carbon emissions from peat fires and improved parameters to calculate those emissions from each part of the combusted landscape more accurately, together with some preliminary results on what the actual emissions likely are and trajectories in terms of how that would influence Indonesia's emissions long-term.

ASSESSING CARBON POOLS BASED ON DIFFERENT FIRE FREQUENCIES

The first study under this project aimed to account different carbon pools and their changes in peatland based on their fire frequency. Subsequent findings described here reflect what has been reported in Volkova et al. (2021).

An initial literature review was conducted to better understand the gaps in knowledge, which revealed that especially aboveground fuels and peat itself have not been sufficiently covered in scientific studies. In the case of aboveground fuels only three studies covered all aboveground fuels, only two measured the pre-and post-fire difference and less than five studies reported losses of aboveground fuels resulting from multiple fires. Meanwhile, less than 10 studies report information of critical peat loss and even fewer analyze these changes following one or more fires.

In contrast to this, in the past two decades about 12% of peatlands in Sumatra and Kalimantan have been burned more than once, and about 23% of that area more than twice (Vetrita et al., 2020). Additionally current peat emission estimates do not account for the production of pyrogenic carbon (PyC; Volkova et al., 2021).

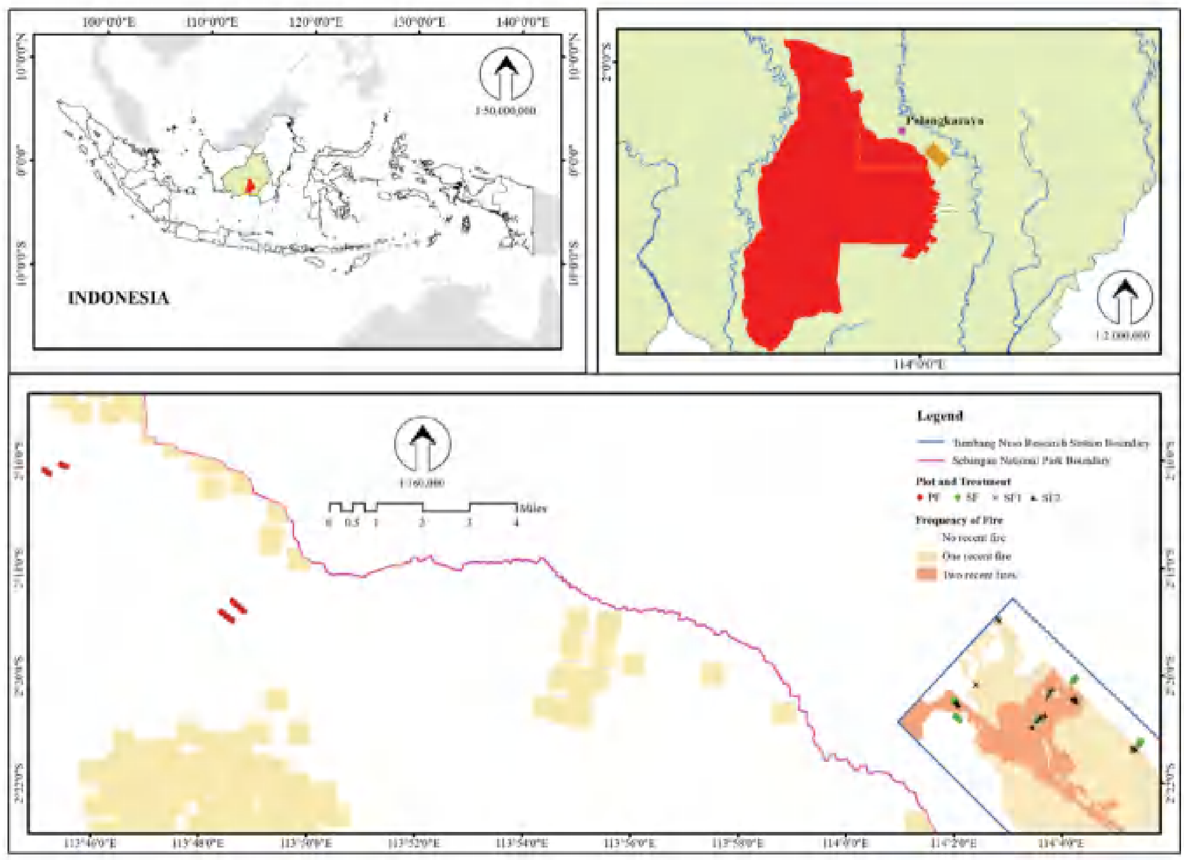


FIGURE 5.2: Study site location (Volkova et al., 2021)

The project team set out to gather data from secondary peat swamp forests (PSFs) in different stages of degradation – long unburned (fire in 1997), once burned and twice burned – to measure fuel loads on the island of Kalimantan. Live trees, standing dead trees, coarse woody debris (CWD), ground cover (grasses and small shrubs), litter, PyC, the top peat layer (0 – 10cm), the medium peat layer (10 – 50cm), deep peat (50 – 100cm), 100+cm peat and the mineral soil surface were collected. For a detailed description of the sampling design in each forest type, refer to Volkova et al. (2021).

These data points were then analyzed to understand the relationship between fire intensity, fuel type, and forest degradation stage to calculate emissions for peat swamp forests at different stages of fire recovery. As such, live tree biomass and dead tree biomass were calculated using an allometric equation for mixed species in Indonesian peat swamp forests, where for dead trees the lack of foliage and branches was adjusted for. Ground cover, litter and PyC were measured on a dry-weight basis.

Results of this analysis shows that both fire frequency and time passed since the last fire had major impacts on the distribution of carbon across aboveground pools. Overall, long unburnt forests stored more aboveground carbon than forests affected by recent fires. One fire reduces aboveground carbon in average by 20%, while repeated fires consumed a further 55%.

Overall, the research revealed that about 90Mg C/hm^2 remain aboveground as the deadwood carbon pool, a finding similar to others (Siahaan et al., 2020). After a 2nd fire, only about a third of the total aboveground carbon as deadwood and PyC is left after two successive fires, whereas about half of the deadwood is retained or transformed to pyrogenic carbon. Litter amount was not affected by time passed since fire. About 3% of aboveground biomass are converted to PyC after one fire and repeated fires increase this amount about threefold, meaning that much of the carbon previously assumed to directly become emissions is actually stored in PyC, leading to overestimates.

For peat, while about 2 to 7 times more carbon was stored in peat than aboveground, an increased number of fires was found to actually increase carbon concentration, possibly a result of PyC eluviating sub-surface and higher bulk density.

RE-EVALUATING COMBUSTION FACTORS

A further study (Krisnawati et al., 2021) estimated the combustion factor for aboveground and peat layer. CF is generally assumed to be 0.5 for aboveground fuels for the first fire and left without guidance for subsequent fires. For organic soils the CF is even 1 (that is 100%, total combustion), which is unlikely since this would require sustained high temperatures throughout the fuel bed (generally not observed). Acknowledging the lack of data, IPCC guidance recommends the development of economy-specific combustion factors, which the project set out to do. It should be noted that this is the first time an economy-level CF was developed.

As such, this research was developed in the same area used by the other study, with the addition of a sampling site of primary peat swamp forest in Sebangau National Park. Sampling design and collection remained the same as in the previous study.

Table 5.1: Study findings on CF differences

Combustion Factors	This study	IPCC default
CF_{AGC}a	0.564	0.50
$CF_{PEAT-10CM}$	0.399	1.0
$CF_{PEAT-20CM}$	0.469	1.0
$CF_{PEAT-30CM}$	0.540	1.0
$CF_{PEAT-40CM}$	0.610	1.0
$CF_{PEAT-50CM}$	0.681	1.0

Assuming that there are no live trees, shrubs or litter remaining immediately after fires. i.e. AGC is estimated as the sum of dead trees + CWD + PyC; CF_{AGC} = Above-ground combustion factor; CF_{PEAT} relating to the different combustion factors for different depth layers ranging from 10 – 50cm (Krisnawati et al., 2021).

The CF was determined through the difference in AGC between and after fires divided by the pre-fire AGC. In this analysis, in contrast to the previous study, small trees (DBH cm), ground cover and litter re-accumulation were excluded to remove deterrent data as the burned sites were not measured immediately after the burn. CF for peat was estimated as the difference in peat mass before and after fires.

Results of the study found that primary forests and long undisturbed secondary forests stored almost twice as much AGC than recently burnt forests, while forests burnt in two recent fires stored a comparable amount in AGC. Primary forests store almost 30% more carbon to 1m depth than secondary forests. Importantly, more than 70 Mg C/hm^2 remained aboveground in form of dead trees, CWD and AGC being largely redistributed aboveground after a 2nd fire, transformed into charred CWD and PyC. PyC, which may account for up to 8% of the AGC after subsequent fires, is currently not included in the IPCC definition of carbon pools and could lead to atmospheric emission overestimation by between 2% and 27% (Santin et al., 2020).

Peat bulk density actually slightly increased, while peat carbon reduced at a far lower share than suggested by IPCC guidelines. Overall, while the IPCC default value for AGC was similar to observed results (0.5 vs. 0.56), the CF for peat widely diverged from default values, ranging from 0.39 to 0.68, while the default value is 1.0. The significantly lower CFpeat found here could mean that Indonesian peatland emissions could be **up to three times** lower than previously assumed.

CONCLUSION AND MOVING FORWARD

The new insights of this project will provide the Indonesian government with powerful new parameters to potentially improve their emissions estimates from peatland fires, which may significantly impact their international reporting to the UNFCCC. In order to aid this decision-making process, the project will develop policy recommendations for emission reduction in these forests. Model integration and trade-off analysis will allow staff the Ministry of Environment and Forestry to understand the consequences of moving to a higher Tier in reporting emissions from peat fires.

Chapter 6

DEVELOPING EQUATIONS TO ESTIMATE STANDING TREE CARBON

Project title: To Demonstrate the Development and Application of Standing-Tree Carbon Equations to Improve the Accuracy of Forest-Cover Carbon Stock Estimates in Thailand

Supervisory agency: Royal Forest Department, Bangkok, Thailand

Executing agency: Kasetsart University Faculty of Forestry, Bangkok, Thailand

Total budget (USD): 253,345

APFNet grant (USD): 199,045

Start date and duration: January 2017, 01/2017-12/2018

Target economy: Thailand

Site location: Ngao Demonstration Forest, Lampang Province, Thailand

Contacts: Kasetsart University: Dr. Khwanchai Duangsathaporn (fforkcd@ku.ac.th)

OBJECTIVES:

- Provide accurate information on national forest carbon stocks to support the decision-making of sustainable forest management policy and to balance public debate on the benefits of forests in climate change mitigation;
- Pilot-test the development of accurate standing-tree carbon equations and their application to the preparation of a forest-cover carbon stock map in the Ngao Demonstration Forest, Lampang Province.

KEY ACTIVITIES:

- Methodology to construct new tree carbon equations;
- Application of tree carbon equation to prepare a carbon cover map;
- Action plan to construct and promote national standing-tree carbon equations;
- Dissemination of project information and knowledge among stakeholders.

INTRODUCTION

Any type of carbon measurement depends on fundamental presumptions, variables, and values to determine the amount of carbon per unit in a given condition. However, as was already shown in the previous chapters, these assumptions may be out of date or based on inadequate or improperly calculated data.

Thailand is facing a similar conundrum. While Thailand has now been reporting to the UNFCCC for a number of years, there is still some uncertainty about the accuracy of national estimates of Thailand's above-ground forest carbon stocks, including incomplete reporting and limited knowledge of the best method to assess carbon stocks. Consequently, this has an impact on Thailand's ability to evaluate its own role in climate change.

Thus, in January 2017 APFNet funded a project spearheaded by the Kasetsart University Faculty of Forestry (KUFF) to develop a methodology for new standing-tree carbon equations that are expected to result in more accurate data about the forest carbon stocks of Thailand. Subsequently, a pilot map of forest cover carbon stocks in the Ngao Demonstration Forest (NDF) in Lampang Province was developed based on the newly calculated stocks per forest type correlated with an NDVI map, which can later be scaled up for the entire economy.

TAKING STOCK OF THAILAND'S FORESTS

In 1992 the researchers Pochai and Nanakorn developed local tree volume equations based on upper stem diameter measurements of standing trees. While a good tool at the time, those equations were developed for only one local area in northern Thailand using a small sample of trees. Additionally, for some of these local tree volume equations only the DBH of the trees was used as an independent variable, while tree height – now the minimum standard for the development of any fundamental volume equation – was simply not considered at all. Additionally, past equations were focused on areas to be logged, thus mostly incorporating large trees, rather than a range of tree sizes. Especially after the national logging ban, and with many (managed) areas now mostly consisting of small and medium diameter trees, the equations should be optimized for a wider range of tree sizes. Sets of species were simply grouped together by tree family, grouping them based on wood density, thus potentially skewing the accuracy of the equations. Finally, to estimate the carbon content in the trees from these volume equations, the generally assumed carbon/biomass fraction of 0.47 (IPCC, 2006), for converting biomass to carbon, is too general and likely too low as wood density in tree species in Thailand tends to be higher than average. The IPCC indicates that "… higher tier methods may allow for variation with different species, different components of a tree or a stand (stem, roots and leaves) and age of the stand …" (IPCC, 2003). Yet, subsequently those equations were applied on a national scale.

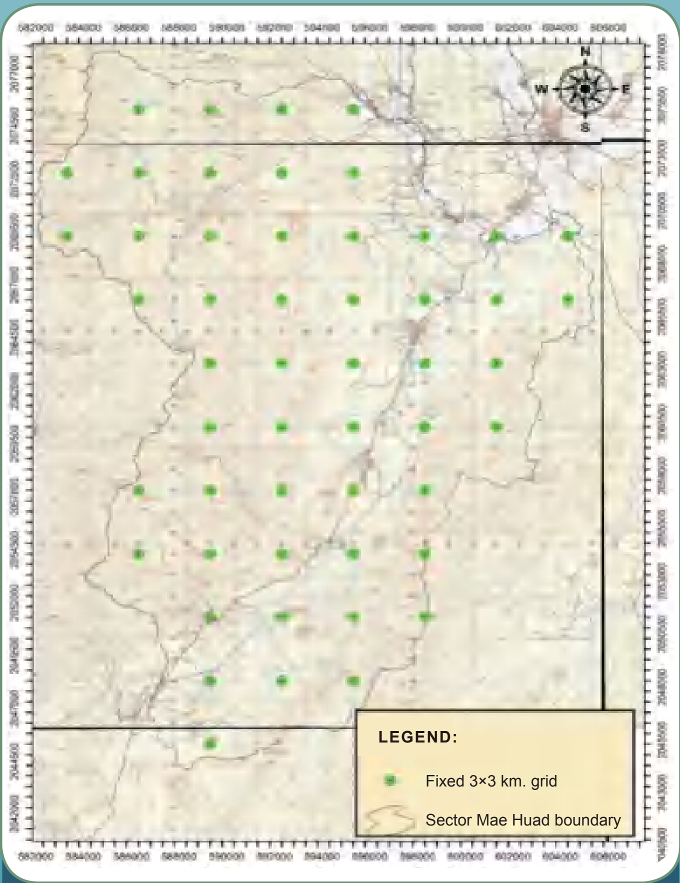


FIGURE 6.1: Map of Mae Huad Sector of NDF showing sample plot distribution (Kasetsart University, 2018a)

With the increasing importance of assessing carbon stocks accurately, these rough calculations were simply not enough anymore and needed to be replaced. Thus a new approach was developed by KUFF to estimate standing tree carbon content as a function of standing tree attributes (meaning incorporating both total height and DBH) and to refine the base equations through taking base sample tree cores.

The data was collected via systematic sampling with a random start and point sample plots laid out on a 3x3km grid (Figure 6.1). A total of 54 sampling points were established. Data recorded included tree species, DBH, height, number and topography.

Via the field data basal area, number of species, wood density by species, IVI (Importance Value Index) were recorded, sub-divided by forest type [such as mixed deciduous forest (MDF), dry evergreen forest (DEF) or dry dipterocarp forest (DDF)]. This way the tree volume and wood carbon fraction calculations for major tree species groups subdivided by wood density in evergreen, mixed-deciduous and dry dipterocarp forests were developed.

These sub-groups of wood density where then once again grouped into wood density classes ranging for comparatively low wood density to high wood density. Each forest type had 10 wood density classes, of which the range for each differed between forest types. Within each of these wood density classes in each forest type, the species with the highest IVI was selected as the major species to be sampled. So, for example, in MDF the selected major species for the lowest wood density class was *Cananga latifolia*, while in DDF it was *Mitragyna brunonis* and in DEF it was *Duabanga grandiflora*. Of each major species three diameter classes (small, medium and large DBH) were identified. Finally, a total of 450 sample trees, involving 30 major species (10 for each forest type based on density class), 3 diameter classes per major species and 5 sample trees per diameter class per major species were selected. Of these trees DBH, total height, merchantable height and bark thickness were measured. The upper stem diameter was also measured with a Wheeler Pentaprism Caliper by two-meter sections up to the first major branch to calculate the tree whole bole wet volume. Using an increment borer, a total of 724 wood samples were collected (note that originally 900 were planned, but due to similar species there were a number of duplicates that did not need additional wood samples). Upper stem diameters of the sample trees were also taken to calculate tree whole bole wet volume and subsequently convert it into whole-bole carbon content based on the wood sample ratio of carbon content to wet volume using combustion technique.

The data obtained from the samples relating above-ground tree carbon to standing tree attributes was fitted into regression equations. These equations were purely for standing tree carbon, not including litter and other CWD or soil carbon. A total of 24 tree carbon equations were constructed, 10 for MDF, 6 for DDF and 8 for DEF.[a]

In addition, general equations for all wood density groups in the different forest types were constructed as well, bringing the total of the tree carbon equations up to 27. Finally, an overarching generic equation for the entire experimental forest was developed.

The new equations predicted significantly different carbon contents compared to the old equations, often with a difference of more than 30%. Carbon/biomass fractions also showed a significant range compared to the IPCC standard fraction of 0.47, ranging from 0.45 to nearly 0.5. This clearly illustrates the value of creating the new equations, enabling Thailand to potentially provide much more accurate carbon stock estimates in the future.

Subsequently, an expert group created a national action plan for the development of national standing-tree carbon equations for all the major species groups.

Regarding carbon sequestration, results showed that DDF, with an average basal area of 36 m^2/hm^2 and 740 trees/hm^2 sequesters around 77.21 t/hm^2, while MDF (basal area 20.9 m^2/hm^2, 783 trees/hm^2) sequesters around 39.88 t/hm^2 and finally DEF (15 m^2/hm^2, 87 trees/hm^2) sequesters around 8.54 t/hm^2.

[a] Note that it was not 10 per forest type as some of the density ranges overlapped, so some of the same equations could be used for different forest types.

APPLYING THE EQUATIONS TO CREATE CARBON STOCK MAPS (Figure 6.2)

In order to apply the equations to create carbon stock maps, basic remote sensing data, such as existing satellite data of the project area [Landsat-8 Operational Land Imager (OLI), Thermal Infrared Sensor (TIRS)] were obtained, resulting in nine spectral bands with a spatial resolution of 30 meters for band 1 to 7 and 9. The project attempted to classify those forest areas into different forest types and the other land use classes using satellite imageries and available aerial photographs, especially from Band 8 (Panchromatic 15m resolution).

Next, the normalized difference vegetation index (NDVI) was generated by means of the normalized vegetation index, which is a spectral transformation of two image bands (red and near infrared band), and shows terrestrial photosynthetic activity and canopy structural variations. Monthly data from several years (2015 – 2017) was utilized and the images with the clearest link between NDVI and sample carbon plots were selected. The differences between those links were largely due to cloud cover and growth period (rainy vs. dry season). The NDVI data was able to detect exposed rock and soil; water bodies; areas with sparse vegetation, such as grass/shrub land and farms (low NDVI); dense plantations and dense/mature horticultural crops (medium NDVI); deciduous forest (medium high NDVI); dense humid forest/thick or multiple canopy communities (high NDVI).

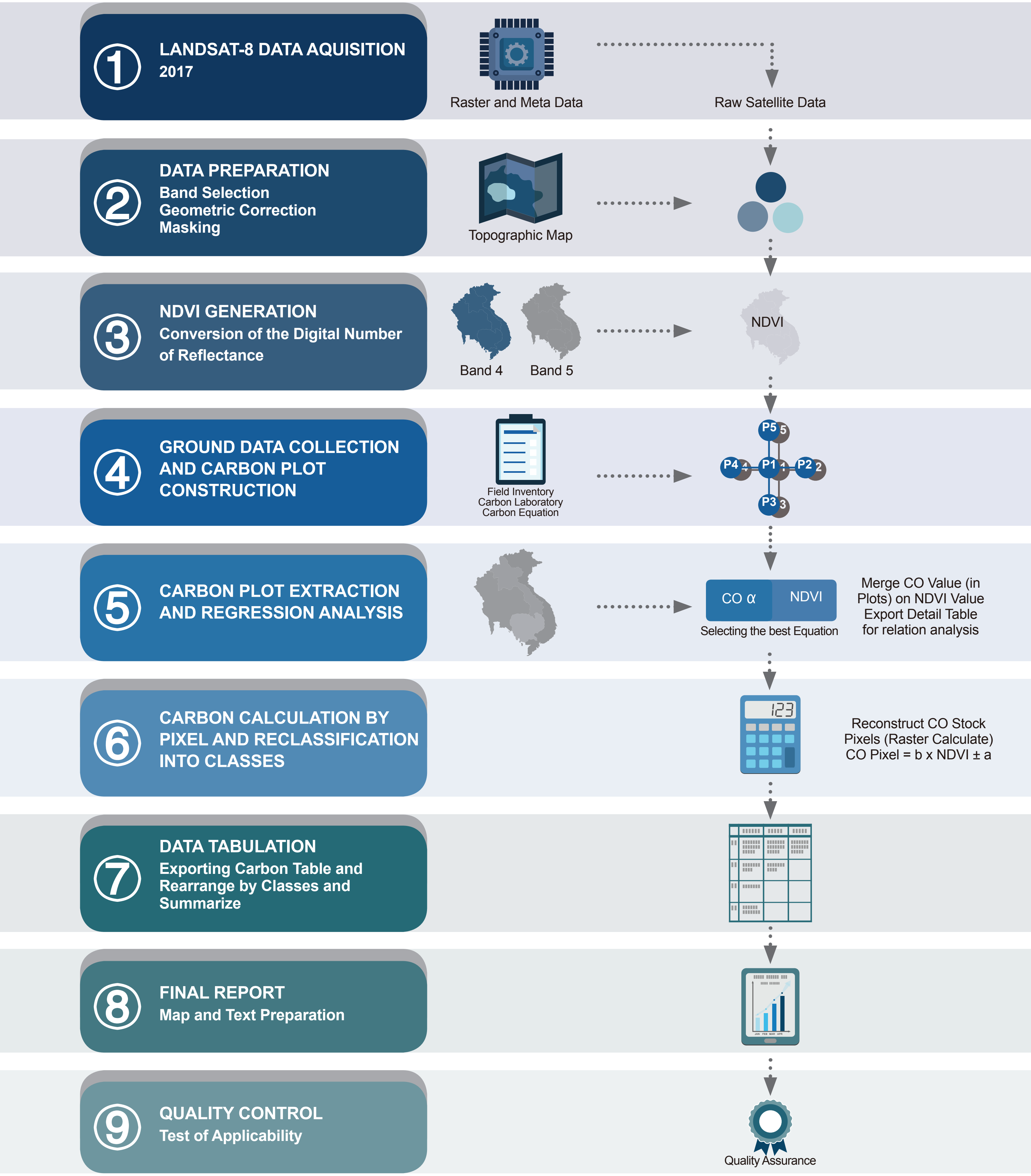


FIGURE 6.2: Flow Diagram of the Entire Process of Carbon Stock Map Generation (Kasetsart University, 2018b)

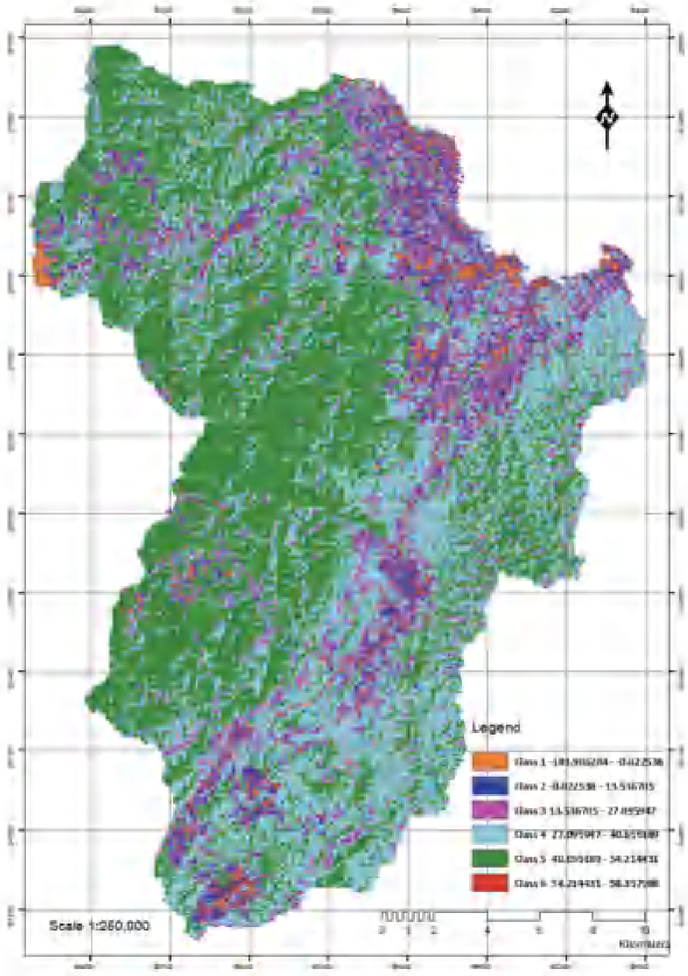


FIGURE 6.3: Carbon stock map of the Mae Huad sector of Ngao Demonstration Forest (Kasetsart University, 2018b)

Following this the NDVI data was used in a linear regression equation to predict the carbon in each pixel for carbon mapping. In parallel, the carbon content from all sample trees in the previously established plots was converted to stand/hm^2 carbon values and applied to carbon stock mapping via their coordinates. To select the best data set of NDVI correlating the closest with the values obtained from the carbon plots, the carbon plots were overlaid on corresponding NDVI raster values of different months. The best fit, producing the highest coefficient of determination, was derived from January 2017.

Following the determination of the best NDVI data set, a regression equation was used for carbon calculation for the entire raster of the project area. The regression model that represented the highest carbon variation by NDVI raster value was used to regenerate carbon in each pixel for entire site. The goal for the regression analysis was to find the relationship between carbon (t/hm^2) and NDVI raster value.

Finally, all carbon raster pixels were reclassified and reconstructed as carbon coverage, resulting in a carbon stock map with six carbon classes (Figure 6.3). The total carbon sink for living standing trees in the Demonstration Forest is estimated at 1,638,728.92 t. Finally, these results were compared with data from a 2nd carbon inventory. Differences were minimal, thus verifying the original approach.

Photo: KUFF

CONCLUSION

The new methodology to estimate standing tree carbon has provided Thailand with a much more sophisticated and accurate option for estimating a key aspect of the forest carbon reporting for international climate change bodies. The subsequent carbon stock map provided a useful tool to visually illustrate carbon stocks and estimate total carbon stocks for an area with the help of GIS. While it does not include other above- and below-ground biomass, such as litter or soil carbon, accurate tree estimations are the first step to providing a more complete picture of the carbon stored in the forests of Thailand.

However, these new approaches have only been developed for and tested in a small part of Thailand in a designated demonstration forest and now need to be scaled up to the national level. This includes the calculation of equations for other forest types and tree species groups not represented in the demonstration forest via the development of a national action plan, which was already developed through the project and submitted to the Ministry of Natural Resources and Environment, that will further publicize it to interested agencies. Some considerations outlined in the *National Action Plan* to continue the upscaling work include:

① Divide Thailand into five geographic regions (North, North-east, East, West & Central, South) and identify the forest types in each region.

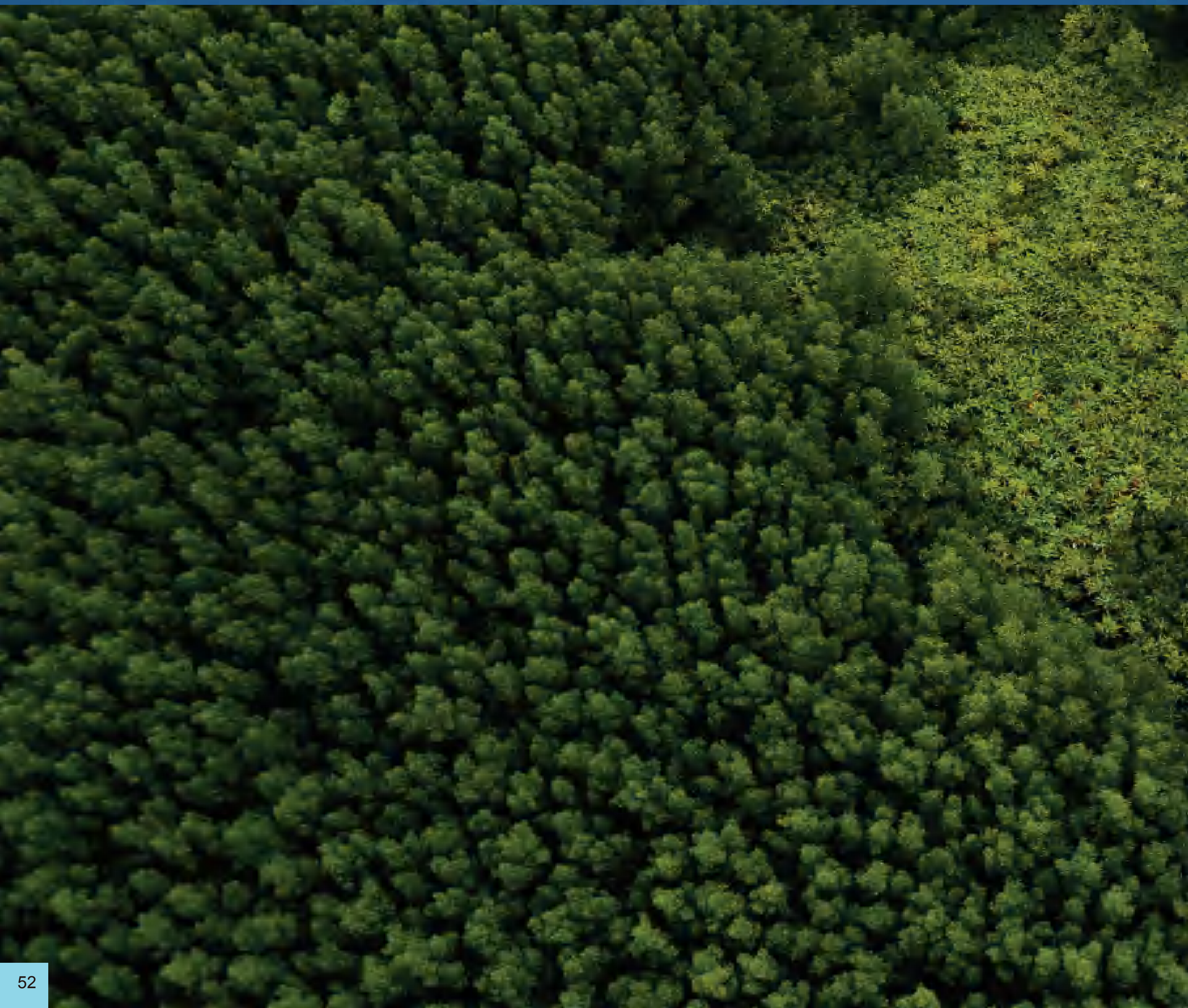
② Use the project methodology to create new tree carbon equations and maps for each forest type within each region (as the small project area of Ngao Demonstration Forest is not guaranteed to be representative for all of Thailand).

③ Get the new tree carbon equations and maps formally approved on national level and into the IPCC reporting process.

If realized, on a national level, Thailand will able to use the more accurate calculation methods, possibly move reporting tiers and thus more effectively battle climate change.

Chapter 7

ASSESSING FOREST CARBON STOCKS BEFORE AND AFTER RESTORATION PRACTICES



Project title: Demonstration of sustainable forest management and restoration in hilly and low mountain areas of southern China [Project ID: 2016P2-CAF]

Executing agency: Research Institute of Forestry, Chinese Academy of Forestry

Implementing agency: Forestry Department of Anhui Province through Qingyang Forestry Bureau, and Forestry Department of Zhejiang Province through Lin’an Forestry Bureau

Project duration: January 2017 - December 2020 (extended to October 2021)

Total budget (USD) : 1,410,270

APFNet grant (USD) : 695,207

Location: Qingyang, Anhui Province; Lin’an, Zhejiang Province, China

OBJECTIVES:

- Promote sustainable forest management and demonstrate effective forest restoration and rehabilitation approaches for degraded forests in hilly areas of southern China.

EXPECTED OUTPUTS:

- Effective technical methods and strategies for sustainable forest management (SFM) and restoration of forests at the landscape level will be developed and demonstrated;
- Carbon accounting methodology for SFM and restoration at the project level will be established;
- Exchange of knowledge and experience in SFM and restoration in the Asia-Pacific region will be promoted.

INTRODUCTION

As previously mentioned, China committed to reach its carbon emissions peak by 2030 and become carbon neutral before 2060. Absorbing and capturing carbon with China's abundant forest resources is one of its strategies to achieve this goal. Chinese forests capture more than 900 million tons of carbon annually, which amounts to 8% of the annual industrial carbon emissions (Jiang, 2022). As forest cover continues to expand in China through tremendous restoration efforts, carbon storage in forests will play a critical role in helping China to achieve its carbon goals. Although CCER (Chinese Certified Emissions Reductions), China's voluntary carbon market, was launched in 2021, the trade of forest carbon credits has been marginalized. Forestry projects successfully selling carbon credits have been unprecedented in China. Developing certified methodologies on accounting forest carbon stocks is the prerequisite for a project to sell its carbon credits in the Chinese carbon market.

Hilly and low mountain areas of Southern China have humid conditions and therefore great forest productivity and carbon sequestration potential. However, forest degradation has been an issue in Lin'an District in the Northwest of Zhejiang Province. A dense population and the pursuit of economic growth has resulted in degraded forests, that is forest stands dominated by a single species, mostly Chinese fir (*Cunninghamia lanceolata*) or hickory (*Carya cathayensis*). In addition to the aforementioned challenges, forest restoration in Qingyang County, Anhui Province, is also impeded by hilly landscapes and barren soil, with a forest cover as low as 30 percent in many areas of the county, making forest restoration an even trickier endeavor.

To restore the degraded forests in Lin'an District and Qingyang County and demonstrate practices to increase forest carbon stocks, Started in 2017, APFNet worked closely with the Research Institute of Forestry Chinese Academy of Foestry, the Chinese Academy of Forestry, the Forestry Bureau of Lin'an District, and the Forestry Bureau of Qingyang County, to launch a project called "Demonstration of Sustainable Forest Management and Restoration in Hilly and Low Mountain Areas of Southern China". In this project, a forested area of 160 hm^2 in Lin'an District and Qingyang County were selected to demonstrate effective forest rehabilitation strategies and SFM models and to calculate carbon sinks for SFM on the project level, aiming to increase the biodiversity of forest and forest carbon storage, improve living standards of residents, and control pests and diseases. As efforts of measuring forest carbon before and after restoration activities have been rare in Southern China, this project sets an example of measuring carbon on the ground.

Various restoration models were adopted in this project, including restoring degraded rocky mountain areas, cultivating large-diameter Chinese fir, planting evergreen broadleaved species in Chinese fir forests, planting deciduous broadleaved mixed species in Chinese fir forests, restoring low-yield moso bamboo plantations, planting mixed income-generating species in hickory forests, planting *Polygonatum sibiricum* in hickory forests, and restoring Chinese *torreya* plantations. To assess the impacts of restoration, especially carbon sequestration, the project. team conducted forest inventories in all of these models with the following methods.

METHODS

In Qingyang County, two vegetation samplings were conducted in 2017 and 2020, prior to and three years after the restoration activities have been conducted respectively. The first sampling was to acquire baseline data of carbon pools in the demonstration areas, and the second one was analyzed to compare changes of carbon storage of trees, shrubs, herbs, litter, and soil. In Lin'an District, one sampling was implemented in 2020 and included control plots besides plots of restoration models. The team collected data in 63 sample plots across 8 restoration models and control plots, including 27 plots in Lin'an District and 36 in Qingyang County. The field survey included measuring the DBH (diameter at breast height) of trees, tree height, crown width, and the height of shrubs and herbs. Litter and soil (both from 0 – 10 cm deep and below 10 cm) were collected.

This methodology accounts for AGB, litter, and soil carbon, while below ground biomass and CWD were omitted. The following equations were applied to calculate carbon in different pools and evaluate the change of carbon storage:

① Net carbon sink:

$$C_t = \Delta C_{t,ij} - \Delta C_{BSL,t} \qquad (7.1)$$

C_t Carbon storage accounted by activities in year *t* (t CO_2-e.a^{-1})

$\Delta C_{t,ij}$ The change in Ct in year *t* (t CO_2-e.a^{-1}) among which *i* =1,2,3,4, represents each carbon pool (trees, shrubs and herbs, litter, soil and harvested timber); *j* represents different management models.

$\Delta C_{BSL,t}$ The change of carbon storage in year t compared to the baseline scenario (t CO_2-e.a^{-1})

t Years since restoration activities (a)

② Carbon storage of vegetation:

$$C_V = Biomass \times carbon\ content \qquad (7.2)$$

③ Carbon storage of litter:

$$C_L = Litter\ stock \times carbon\ content \qquad (7.3)$$

④ Organic carbon density in soil:

$$SOC = \sum_{i=1}^{n} P_i \times C_i \times T_i/10 \qquad (7.4)$$

SOC Soil Organic Carbon (t/hm^2)

P_i Soil volume in layer *i* (g/cm^3)

C_i Organic carbon content in layer *i* (g/kg)

T_i Soil depth in layer *i* (cm)

n Number of soil layers

RESULTS AND IMPLICATIONS

The project team has established baseline values of carbon sinks for each demonstration site. The total carbon storage of the project sites in Lin'an District is 430,570 tC, and the total carbon storage of all project sites in Qingyang County is 17,745,617 tC. The annual increment of carbon storage changes from 1,442 tC/hm^2 to 3,300 tC/hm^2 depending on the restoration model. An increase in carbon storage was observed across the rocky mountainous area in multiple sites. For instance, total carbon storage has the largest increment at the site of restoring low-yield moso bamboo plantations, amounting to 18.43 tC/hm^2 (Figure 7.1). This is because moso bamboo is a fast-growing species and accumulated more biomass than other species over the project period. The carbon sink of the demonstration site, where large-diameter Chinese fir was cultivated, increased to 5.65t/hm^2, benefited from the increased sunlight after thinning. There was also an increase in soil carbon at some sites. For example, the site of ecological management of Chinese *torreya* has gained 4.59 t/hm^2 of soil carbon over the course of four years.

The research results, while preliminary, indicate that most models adopted by the project have increased carbon sequestration in forests. When restoration projects are conducted in similar ecosystems with a goal of capturing and storing carbon, these models could be applicable. Additionally, the research results can help forest owners to estimate their carbon storage and potentially sell their carbon credits on the carbon market. This methodology has established a potential to increase the livelihoods of forest-dependent residents and promote forest restoration in Southern China, where some rural populations would benefit from gaining additional income from selling carbon credits.

Additionally, the Research Institute of Forestry, Chinese Academy of Forestry has developed the *Carbon Accounting Methodology for Forest Restoration*. This methodology contains the definition of reference levels for forest restoration based on the estimation of carbon sinks in project plots. The methodology is especially valuable since it accounts for small-scale forest carbon sinks on a project level, especially in family-managed forests and cooperative-managed forests. Promoting this methodology will contribute to combating climate change in China.

FIGURE 7.1: Moso bamboo plantation before and after project implementation
Photo: Research Institute of Forestry, Chinese Academy of Forestry

Chapter 8

INVENTORY-BASED FOREST CARBON ESTIMATION AT THE FOREST MANAGEMENT UNIT LEVEL

INTRODUCTION

As already mentioned in Chapter 2, the inventory-based estimation of forest vegetation carbon stocks is a group of classical study methods of carbon accumulation within forest ecosystems (Fang et al., 2001; Shao et al., 2017). These methods are applied based on forest inventory data, such as forest type, stand age, stand density, stand volume, mean tree height and DBH (Tang et al., 2018). Moreover, the methods used to estimate forest biomass and carbon stocks vary depending on the estimation scale (Shi et al., 2017). In the past decades, allometric equations, the mean biomass method and volume-derived methods were most commonly used for estimating vegetation carbon storage based on inventory data. Each method has its unique advantages and disadvantages, and there is no one-size-fits all approach, no one method is ideally suited for all estimation goals from individual tree to large scale forest.

State-owned forest farms are important forest management units in China, a total of 4,855 forest farms are currently managing 56.67 million ha forest land, that is more than a quarter of the total forest area in China. Many researchers in China have assessed different biomass estimation methods for national level or large scales, however, there are few studies focusing on forest farm-level carbon estimation. Accurately and efficiently quantifying forest carbon stocks and forest carbon carrying capacity at the forest farm level is crucial to understand their potential in mitigating climate change, as well as to contribute to the 2060 carbon-neutrality commitment of China as carbon sinks. In this context, APFNet selected two forest farms in China to estimate the current forest carbon storage based on two different forest inventory methods, one focusing primarily on an inventory-based approach, while the other using a model-based approach that also can forecast carbon carrying capacities in the future, and explore the effective forest management options to increase carbon storage capacities, while at the same time balancing it with other forest values.

WANGYEDIAN FOREST FARM: ASSESSING FOREST CARBON STORAGE THROUGH AN INVENTORY-BASED APPROACH

Project title: Study on forest carbon storage and carbon sink potential of Wangyedian Forest Farm [ID: 2021P2-INM]

Supervisory agency: Forestry and Grassland Administration of Chifeng City

Executing agency: Wangyedian Forest Farm

APFNet grant (USD): 169,559

Start date and duration: September 2021, 09/2021 – 08/2022

Target economy: China

Site location: Kalaqin Banner, Chifeng City, Inner Mongolia, China

Contacts: Project Director: Ma Chenggong (13947673426@qq.com)

EXPECTED OUTPUTS:

- Complete the forest inventory of Wangyedian Forest Farm;
- Estimate forest vegetation carbon storage and analyze forest carbon sink potential based on forest resource subclass survey data;
- Develop a multi-functional forest management plan for Wangyedian Forest Farm.

In September 2021 APFNet started a project entitled “Study on Forest Carbon Storage and Carbon Sink Potential in Wangyedian Forest Farm”. The overarching goal of the project is to estimate the current forest carbon storage of Wangyedian Forest Farm (WYDFF), forecast the carbon storage capacities of the farm in the future, and explore the most effective forest management options to increase carbon storage capacity and at the same time balance it with other important forest ecosystem services. As such, the project will develop a forest management plan to optimize the silvicultural forest management practices to promote a multifunctional forest management effect in WYDFF, where the carbon storage capacity will be incorporated in the plan as one of the management objectives.

STUDY AREA

Wangyedian Forest Farm, owned by the state and located at the outskirts of Chifeng City, Inner Mongolia, is the project site (Figure 8.1). WYDFF manages roughly 25,000 hm^2 of forests, the main types of forest plantations include larch (*Larix principis-rupprechtii*, *Larix olgensis*), Scots pine (*Pinus sylvestris*), and Chinese pine (*Pinus tabuliformis*). Additionally, there are natural secondary forests of Mongolian oak (*Quercus mongolica*), poplar (*Populus davidiana*), Dahurian birch (*Betula dahurica*), Asian white birch (*Betula platyphylla*), and others. The coordinates of WYDFF are 118°09’ – 118°30’E and 41°21’ – 41°39’N with the central point at 118.3825°E, 41.5543°N (Xu et al., 2018). Influenced by a temperate continental climate, the region has an annual precipitation of 300 – 500 mm and an annual average temperature of 4.2 °C (Xinyu Li et al., 2020). The elevation is between 500 and 1,890 meters above sea level with over 85% of its land classified as mountainous. Its soil types mainly include brown soil, cinnamon soil, meadow soil, black soil in the mountainous area, among which brown soil covers most of the area (Yan et al., 2015).

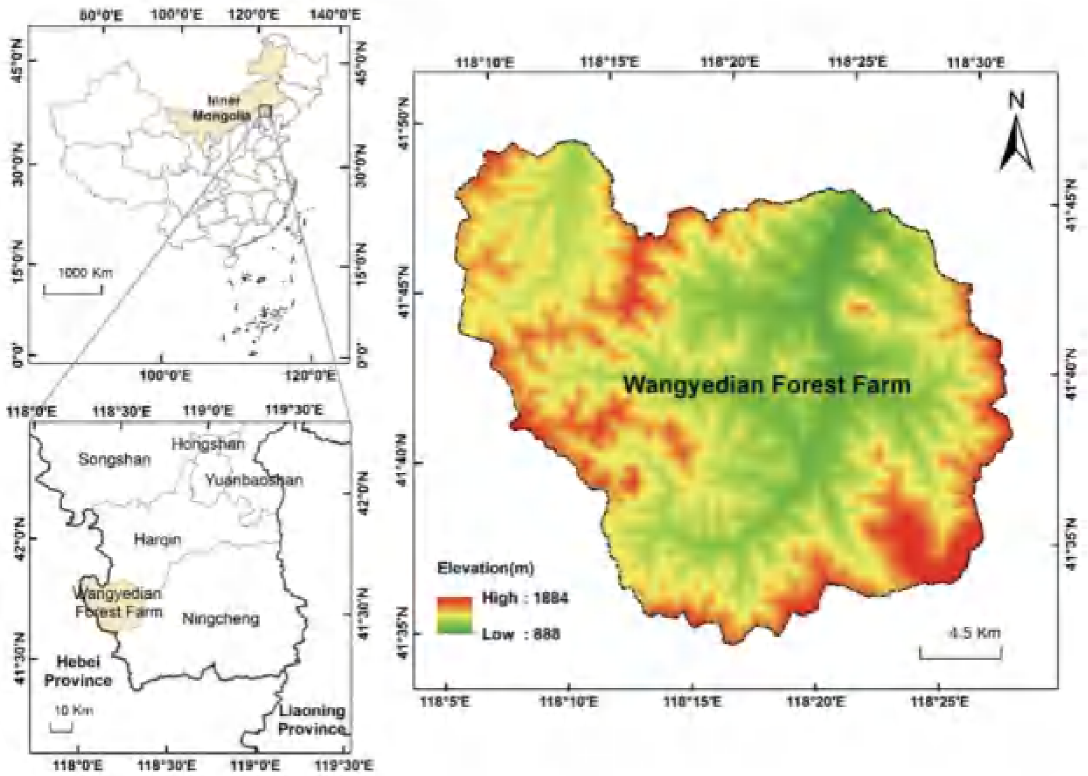
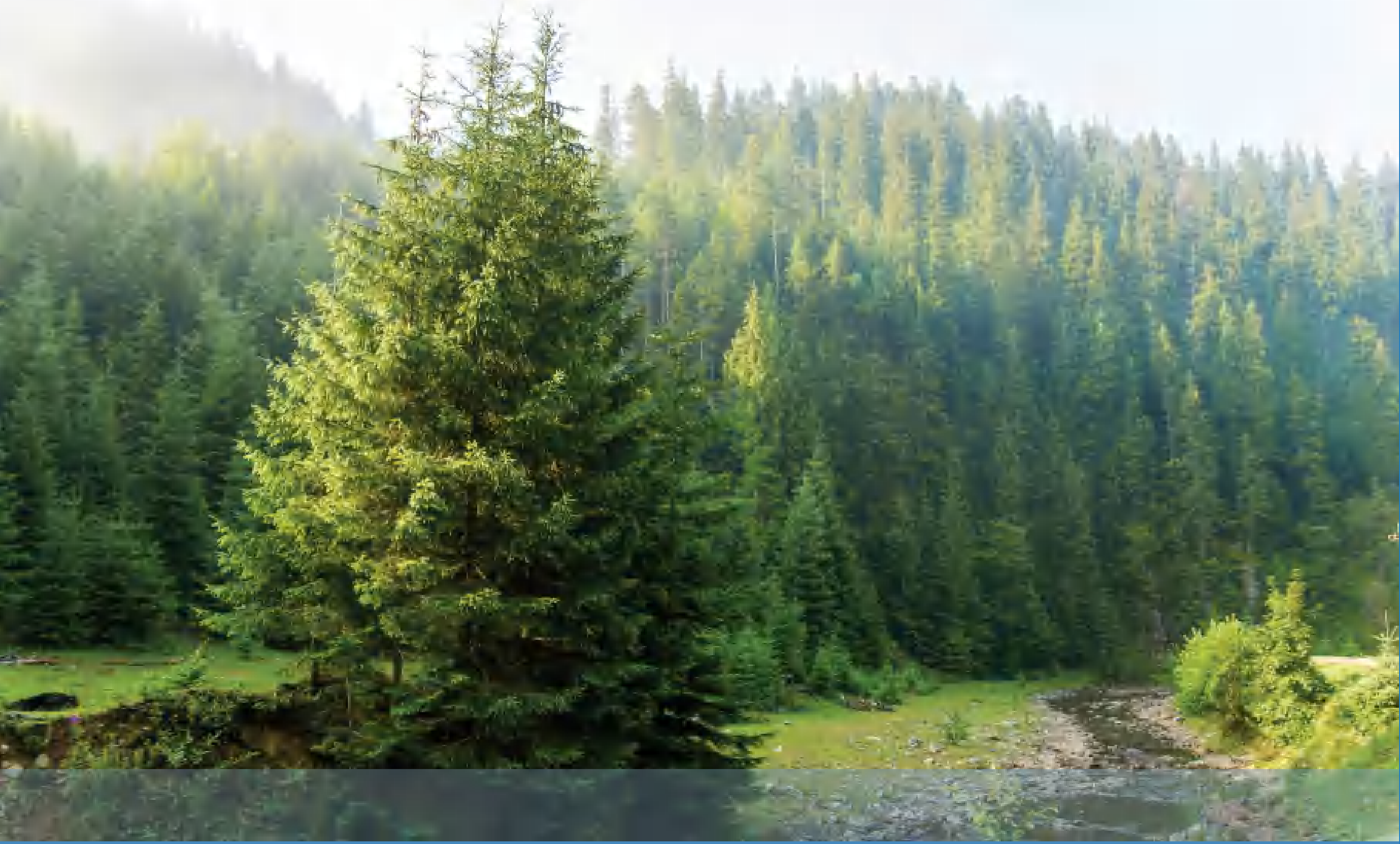


FIGURE 8.1: Location of the study area (Li et al., 2020)



SAMPLING DESIGN AND INVESTIGATION

This study used a stratified sampling approach to set up permanent sample plots in WYDFF. Forest type (also shrub type) and age group (young, middle-aged, near mature, mature and over mature) are used as the two criteria for stratifying the forest area. Based on the previously available forest inventory data, nine forest types [(larch forest, European pine forest, Chinese pine forest, Mongolian oak (*Quercus mongolica*) forest, birch forest, Korean aspen forest, mixed conifer forest, mixed broad-leaved forest and mixed conifer-broad-leaved forest) and three shrub types (wild apricot, hazel, and *spiraea*)] were identified. Optimal allocation or "Neyman allocation" (a procedure for dividing the sample among the strata in a stratified sample survey, which produces the smallest variance for estimating a population mean and total, given a fixed sample size) is used to identify the number of sample plots for each stratum. Totally, 186 permanent sample plots (177 for trees and 9 for shrubs), identified through the stratified sampling method, were used to compare stand level biomass between the identified forest types and specific age groups. The size of each of the permanent sample plots is 600m^2 (24.49m × 24.49m). Specific plot information (GPS, elevation, slope, aspect, forest type, canopy cover) and data of each individual tree (relative location, species, number of trees, DBH, mean height, dominant height, etc.) were collected. In each permanent sample plot, one shrub sample plot (5m × 5m), one grass sample plot (1m × 1m) and one litter sample plot (1m × 1m) were set up in addition to the analysis of the trees to collect data and biomass samples of shrubs and grasses. Soil samples from different depths, specifically 0 – 10cm, 10 – 30cm, 30 – 50cm, were also collected in each permanent plot. The investigation of the permanent sample plots was conducted in September 2021(Figure 8.2).

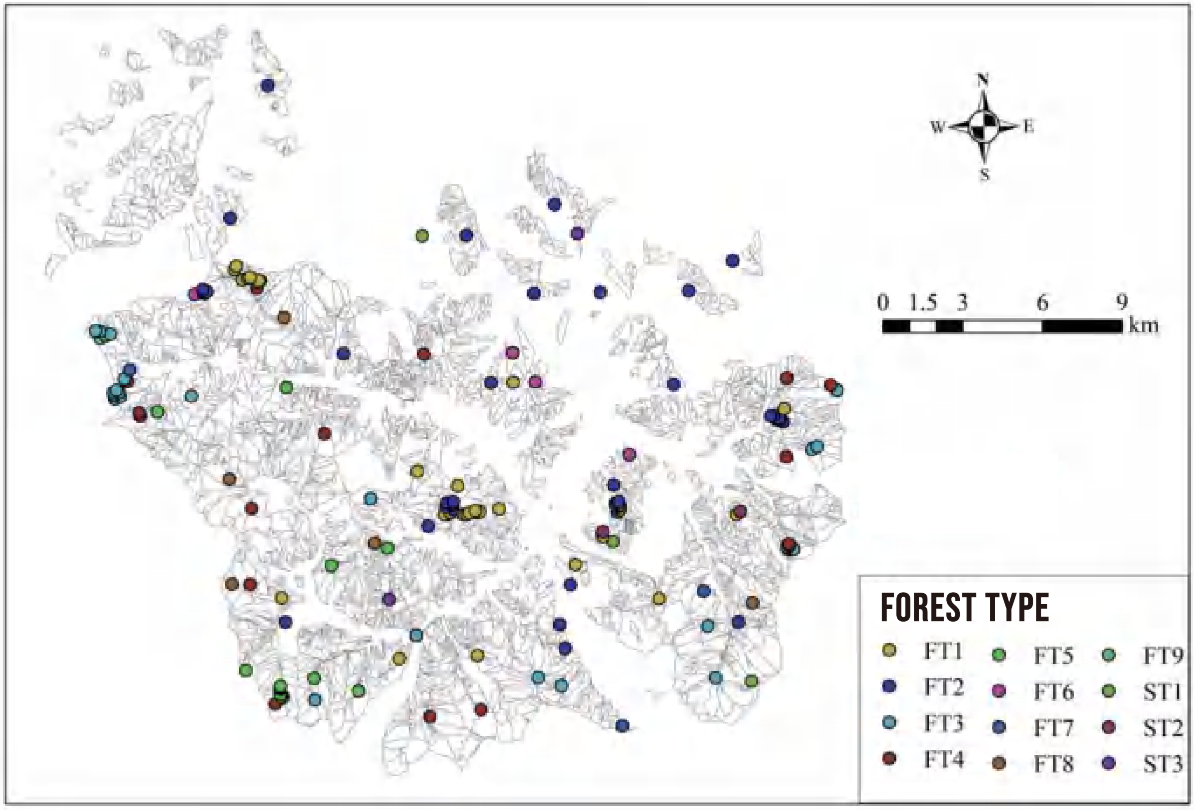


FIGURE 8.2: DISTRIBUTION OF SAMPLE PLOTS IN WANGYEDIAN FOREST FARM
SOURCE: WYDFF

Note: FT1 = larch forest, FT2 = European pine forest, FT3 = Chinese pine forest, FT4 = Mongolian oak forest, FT5 = birch forest, FT6 = Korean aspen forest, FT7 = mixed conifer forest, FT8 = mixed broad-leaved forest, FT9 = mixed conifer-broad-leaved forest, ST1 = wild apricot, ST2 = hazel, ST3 = *spiraea*

There are 199 forest compartments which are subdivided into 3,144 stands in WYDFF area. The size for each stand ranges from 0.1 hm^2 to around 150 hm^2. In order to get a clear understanding of the overall forest resources in the farm and also accurately estimate the size of different forest types and age groups, the study also set up an additional 7,800 temporary strip plots in WYDFF. Basic plot information (GPS, elevation, slope, aspect, forest type, canopy rate, etc.) and information about each individual tree (species, number of trees, DBH, mean height and dominant height) were collected. The total area of the temporary plots was to be above 1% of the total area of the plantation forests and above 3% of the natural forests. The field investigation of the temporary sample plots was conducted between September and December 2021.

CALCULATION METHODS

This project compares and analyzes the most efficient and accurate approach for estimating the carbon stocks of forest ecosystems at the forest management unit level. The aforementioned methods, including the allometric method, the mean biomass density method, the IPCC method, the conversion factor continuous method and the biomass conversion factor method for tree biomass estimation are compared at the forest farm level. The research team assumes the result of the allometric method is closest to the real biomass of the stand trees, since the mean biomass for each of the 3,144 stands in the forest farm will be calculated through allometric equations of certain tree species and data obtained from the field investigation of 7,800 sample plots. The mean biomass density method will first calculate the mean biomass of the different forest types in specific age groups, then the whole biomass of stand trees is derived by multiplying the area of each forest type and age group. The other three methods will either use the constant BEF provided by the IPCC and the continuous BEF provided by other researchers, or the Biomass Conversion Factor (BCF) equations from national standards. Other biomass in the forest ecosystem, including shrubs, grasses, litters and soils, will be calculated separately. The research team also plans to develop continuous BEF equations for each forest type suitable to use in similar areas, which will accurately reflect the relationship between stand volume and total vegetation biomass. While estimating forest carbon stocks, since most scholars assumed that carbon content in plant biomass is constant (Brown, 1997; Matthews, 1993), this study used 0.47 as the carbon content as recommended by IPCC.

METHODS

① Allometric method:

$$M = \sum_{i=1}^{3144} A_i \times m_i, m_i = a \times D^b \quad (8.1)$$

i	The stand
A_i	The size of the stand i
m_i	The mean biomass of the stand, which is calculated from the allometric equation for each individual tree in the sample plots
a b	The coefficients for certain tree species
D	The diameter at breast height

② Mean biomass density method

$$M = \sum_{i=1}^{9} A_{ij} \times m_{ij} \quad (8.2)$$

i	The forest type
A_{ij}	The size of forest type i with age group j
m_{ij}	The mean biomass of forest type i with age group j

③ IPCC method

$$M = \sum_{i=1}^{9} A_i \times [V_i \times D_w \times BEF_2] \times (1 + R) \qquad (8.3)$$

i	The forest type
A_i	The size of forest type i
V_i	The merchantable volume per hectare
D_w	The basicwood density
BEF_2	The constant biomass expansion factor provided by IPCCR
R	The root/shoot ratio

④ Conversion factor continuous method

$$M = \sum_{i=1}^{9} A_i \times V_i \times BEF, BEF = a + \frac{b}{V} \qquad (8.4)$$

i	The forest type
A_i	The size of forest type i
V_i	The merchantable volume per hectare
a b	The coefficients for each forest type (Fang et al., 2001)

⑤ Biomass conversion factor method

$$M = \sum_{i=1}^{9} A_i \times [V_i \times BCF_i] \times (1 + R_i) \qquad (8.5)$$

i	The forest type
A_i	The size of forest type i
V_i	The merchantable volume per hectare
BCF_i	Continuous functions for converting volume to above-ground tree biomass from national standards
R_i	The function of the root-to-shoot ratio

WAYS FORWARD

At the point of writing this report in 2022, the project results were still preliminary, but the research team is intending to estimate the carbon storage within the whole forest ecosystem. Except for tree biomass estimation, specific investigations on shrub and grass layers have been conducted to generate the whole vegetation carbon storage; litter and soil samples were also collected to calculate the litter carbon storage and soil carbon storage. The total carbon stocked in the forest farm will be calculated, which includes the vegetation carbon pools (tree, shrub and grass carbon pools), the litter carbon pool and the soil carbon pool. Growth model-based potential carbon projections will be analyzed for estimating the carbon carrying capacity. A forest management plan to optimize the silvicultural and forest management practices to promote the multi-functional forest management in the farm will be developed while the carbon storage capacity will be incorporated in the plan as one of the management objectives.

WANZHANGSHAN FOREST FARM: ANALYZING FOREST CARBON CARRYING POTENTIAL

A lot of forest carbon storage research ignored forest management and temporal scales, or the temporal scale considered may not be long enough because a forest may be a source of and sink for carbon at different points in time. But, through proper forest management and utilization of wood products, forests can be kept as stable carbon sinks in the long term. In 2021, APFNet used the Forest Simulation Optimization System (FSOS) at Wanzhangshan Forest Farm (WZSFF, located in Pu'er City, Yunnan Province) to analyze the future carbon carrying potential of the farm under different management scenarios. With the developed growth and yield functions of key forest types, FSOS can analyze and compare different management scenarios in WZSFF over longer time periods. The methodology used in this study for calculating the forest carbon storage was following the national guidelines for forest carbon accounting in China, which is using a volume-derived inventory-based carbon estimation approach.

Four management scenarios simulated in this study for the next 100 years are as follow (Figure 8.3):

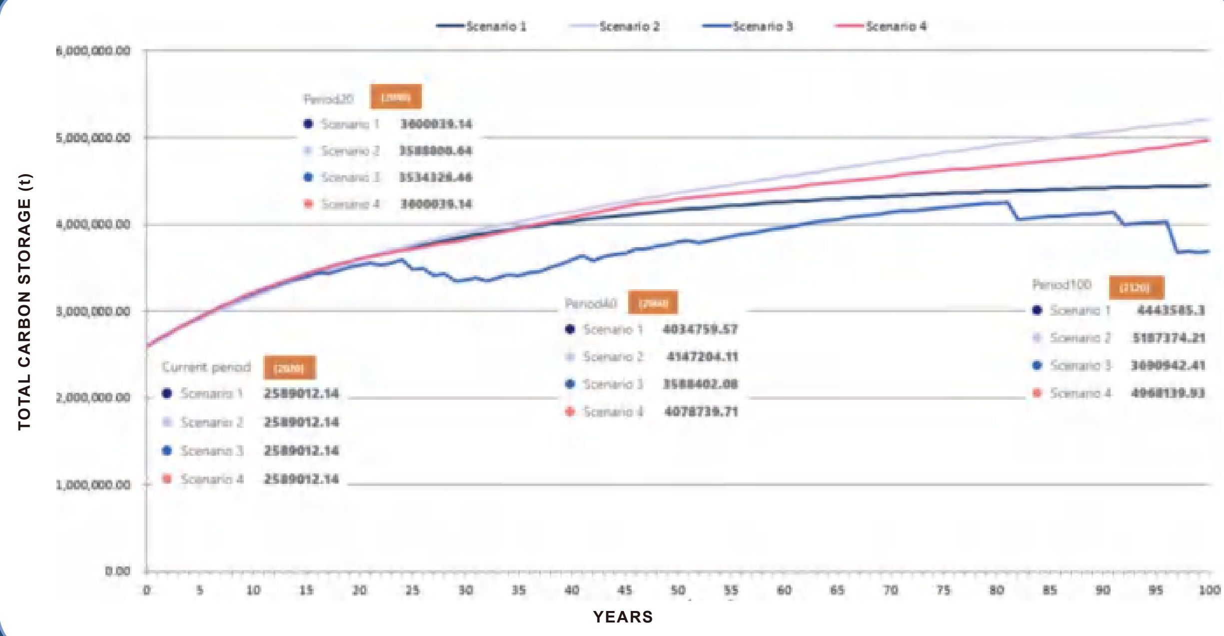


FIGURE 8.3: Comparison of carbon storage in four scenarios

Source: Wanzhangshan Forest Farm

- Scenario 1: Grow naturally, no management, not considering any natural succession.
- Scenario 2: Manage the commercial forest area only.
- Scenario 3: Grow naturally, no management, considering natural succession.
- Scenario 4: Same as Scenario 2, but no harvest is allowed in the first 20 years.

According to the simulation of FSOS, by 2060 the total carbon storage of Wanzhangshan Forest Farm would increase to 4.03 million t (Scenario 1), 4.15 million t (Scenario 2), 3.59 million t (Scenario 3), or 4.09 (Scenario 4) from the current 2.59 million t (Figure 8.4). and the average annual carbon sequestration of the farm is estimated to be 36,000 t (Scenario 1), 39,000 t (Scenario 2), and 25,000 t (Scenario 3). By the year 2121, the carbon storage of the farm is predicted to reach 4.44 million, 5.19 million, 3.69 million and 4.97 million t for Scenario 1 – 4, respectively. The average annual carbon sink of Scenario 2 (26,200 t) is 2.5 times as much as that of Scenario 3 (11,000 t). The average annual timber amount harvested in Scenario 2 can reach as much as 24,000 m^3 in 2121, and the average annual revenue is estimated to reach CNY 28 million (around USD 4.4 million, not adjusted for Net Present Value NPV) with an average annual profit of CNY 22 million (around USD 3.5 million). The social and economic contributions to the local communities of Scenario 2 is much more than Scenario 1 and Scenario 3 because of the timber production.

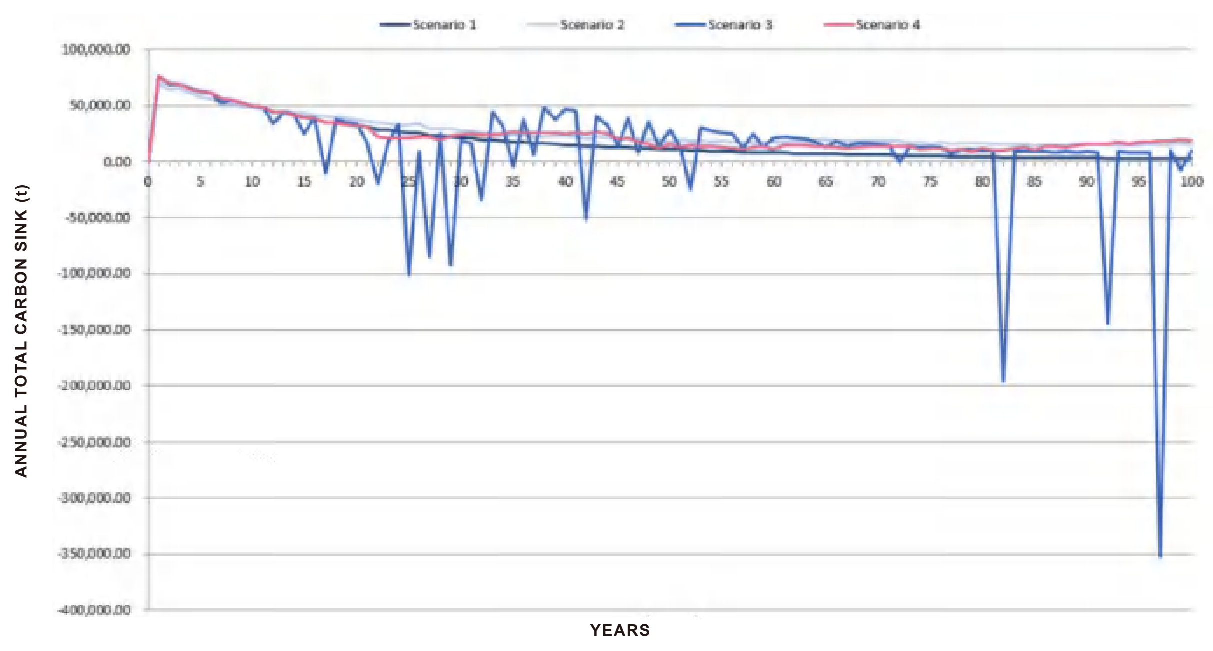


FIGURE 8.4: Comparison of the annual total carbon sink in four scenarios

Source: Wanzhangshan Forest Farm

Chapter 9

GIS-BASED FOREST CARBON STOCK MEASUREMENTS

Project title: Regional Forest Observations for Sustainable Forest Management [2018P2-CAF]

Executing agency: Institute of Forest Resource Information Techniques (IFRIT), Chinese Academy of Forestry(CAF)

Supervisory agency: (a) General Directorate of Administration for Nature Conservation and Protection/ MOE (GDANCP), Cambodia
(b) Guangxi Forest Inventory & Planning Institute (GFIPI), China
(c) Guangxi University (GU), China
(d) Faculty of Forestry of National University of Laos (NUL), Laos
(e) Forest Research Institute Malaysia (FRIM), Malaysia
(f) Forest Department (FD), Myanmar
(g) Royal Forest Department (RFD), Thailand
(h) Forest Inventory & Planning Institute (FIPI), Viet Nam
(i) Southwest Forestry University (SFU), China

Total budget (USD): 699,860
APFNet grant (USD): 499,860
Kick-off date & duration: Phase I: September 2011, 9/2011 – 2/2014
Phase II: July 2018, 07/2018 – 12/2020 (extended to 12/2022)
Target economies: Lao PDR, Cambodia, Myanmar, Thailand, Vietnam, Malaysia, China

OBJECTIVES:

- Further enhance the capacity of regional level forest resource monitoring and analysis through applying medium resolution remote sensing data, analyzing forest changes, and linking the change characteristics with forest polices;
- Enhance the capacity on stand level forest inventory through applying high resolution remote sensing data and airborne laser scanning technology;
- Further strengthen the network of forest monitoring in the region through establishing a mechanism for regional forest observations and providing related capacity building support.

EXPECTED OUTPUTS:

- Forest cover map of 2017 at 30 m spatial resolution;
- Forest change and driving forces analysis during 2005 – 2017;
- Stand level inventory maps using high resolution data on selected sites;
- Estimated forest carbon maps for selected sites using airborne laser scanning technology;
- Establish a mechanism for regional forest observations;
- Monitoring enhanced through the Regional Forest Observations (RFO) mechanism in the region.

INTRODUCTION

To mitigate greenhouse effects, it is essential to provide managers and policy makers with accurate information on the current state, dynamics, and spatial distribution of carbon sources and sinks (Wang GX et al., 2009). As mentioned in Chapter 2, GIS-based spatially explicit approaches have been developed for producing geo-referenced estimates of carbon sinks and stock potential (Chen JM et al., 2003) and are usually employed to process model inputs (land cover, soil texture) and to visualize results.

Among the three main types of datasets to estimate aboveground biomass (optical remote sensing data, SAR, and LiDAR), LiDAR has gained increased popularity in its application in the field of forestry, and is now used in forest mensuration, forest fire management, forest mapping, land classification and other practices by attaching a LiDAR device on a satellite, airplane, backpack, or other vehicles (Figure 9.1, 9.2). Research has indicated that this technology could improve the estimation accuracy of forest height and structure and forest carbon storage (Gwenzi et al., 2014), and, in applying this technology, much time can be saved while also necessitating less staff to be on-site for on-the-ground monitoring.

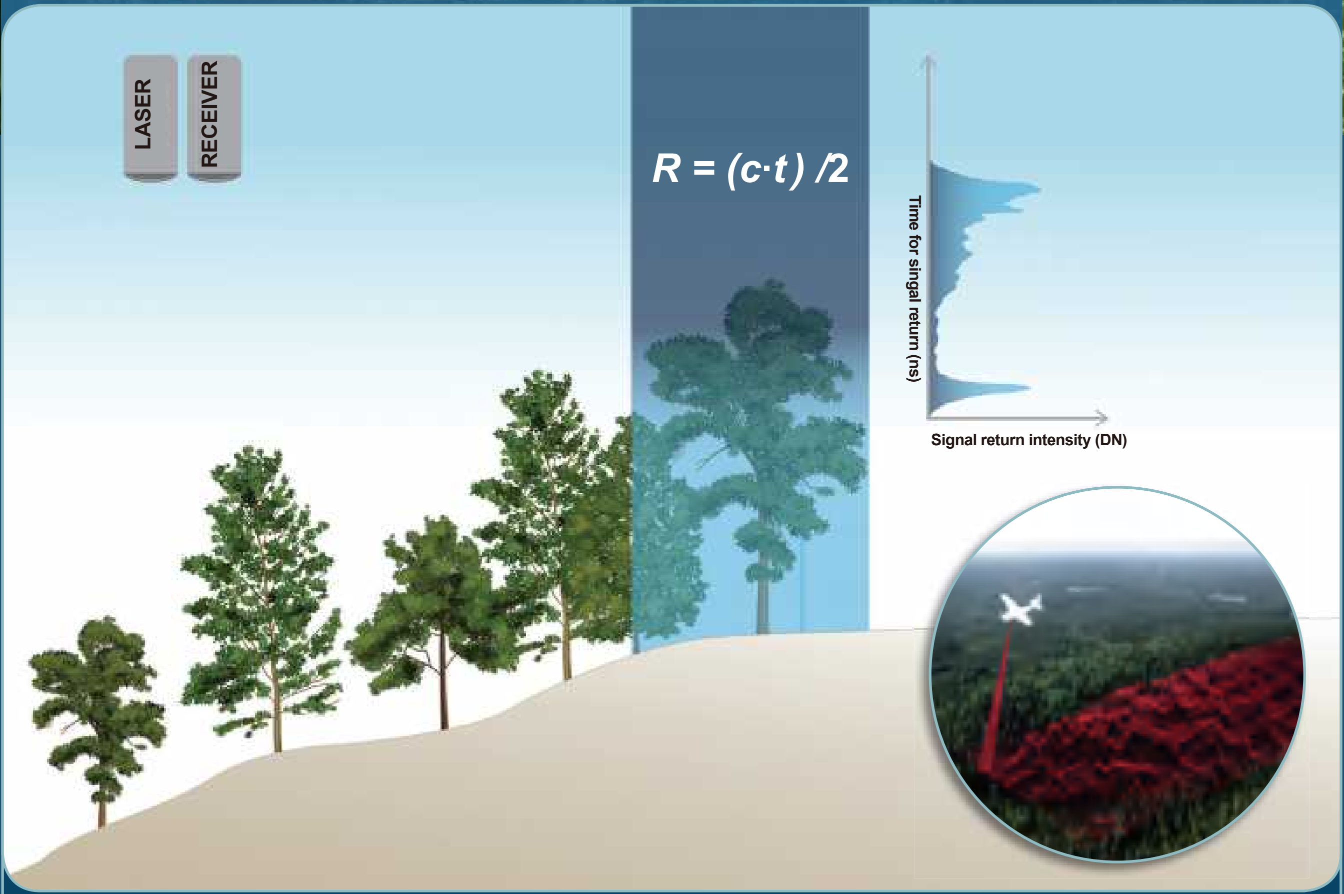


FIGURE 9.1: Lidar remote sensing principle

Source: IFRIT, CAF
Note: Light Detection and Ranging (LiDAR) Laser Imaging Detection and Ranging (Lidar); Range (R) recorded as R=(c·t)/2, R=distance for signal to send and return, C =speed of light), t=time for signal to send and return.

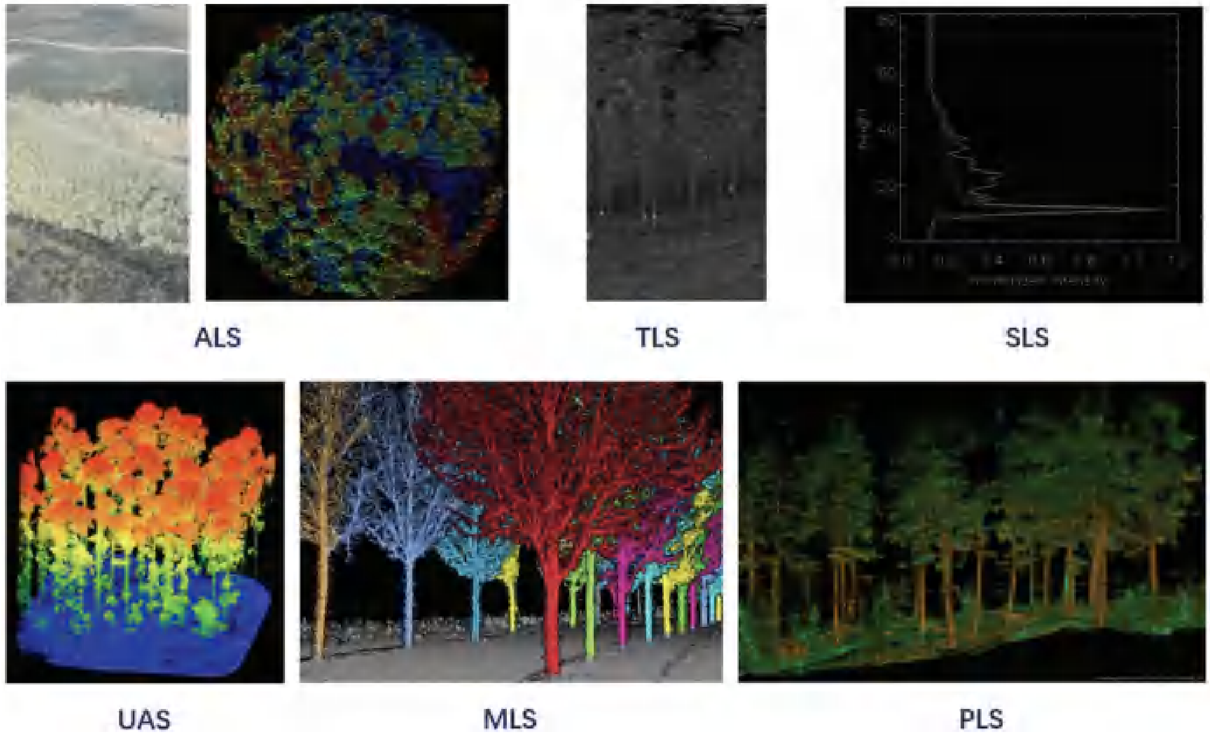


FIGURE 9.2: Photos scanned by Lidar using

Source: IFRIT, CAF
Note: ALS = Airborne Laser Scanning, TLS = Terrestrial Laser Scanning, UAV = Unmanned Aerial Vehicle Laser Scanning, MLS = Mobile Laser Scanning, SLS = Satellite Laser Scanning, and PLS = Personal Laser Scanning.

ASSESSING FOREST CARBON STOCKS IN THE GMS AND MALAYSIA

In order to fill data gaps in the GMS region and Malaysia APFNet funded two phases of the project *"Forest Cover and Carbon Mapping in the Greater Mekong Subregion (GMS) and Malaysia"* (2011 – 2013 and 2018 – 2022) to a develop forest cover map and carbon stock map for the target region. Phase I of the project has developed algorithms for forest cover mapping and carbon estimation and produced forest maps of 2005 and 2010. It also created a forest aboveground biomass map of 2005, which provided an important baseline analysis and assessment on the forest resource change in the region and enhanced the forest monitoring capacity of economies in the GMS. Phase II aimed to further enhance forest resource monitoring on the regional scale in the GMS and Malaysia to identify driving forces for forest change.

Throughout the project, forest resources were monitored on a regional scale, and on selected sites, and the latest high-resolution technology LiDAR was used to obtain a variety of different information. In the project area, where airborne LiDAR data was available, forest parameters (height, canopy density, volume density) for each forest management unit were estimated through the allometry models based on 500 field plots, designed using a stratified sampling method, and LiDAR metrics.

CASE STUDY

Nanning, one of the target sites of the project, is located in Guangxi Zhuang Autonomous Region in the South of China. Its longitude and latitude coordinates are 107°19'E – 109°37'E and 22°12'N – 24°2'N, respectively (Figure 9.3). The total area is about 2,311,200 ha with a forest cover age of 49.5%. Nanning has a subtropical climate with an annual mean temperature of 20.8 – 21.8°C and an annual precipitation of 1,300 to 2,400 mm. The natural main vegetation type is the evergreen broadleaved forest, which is mainly distributed in natural reserves and parks. Current dominating species are eucalyptus, Masson's pine (*Pinus massoniana*), Chinese fir (*Cunninghamia lanceolata*), Formosa acacia (*Acacia confusa*) and star anis (*Illicium verum*) in broadleaved forests.

FIGURE 9.3: Location of the study area

Source: GFIRI, China

DATA COLLECTION AND PROCESSING

The airborne LiDAR data was collected in Nanning from October 2017 to April 2018. The LiDAR scanners RIEGL QV-1560 and LMS-Q680 were used to collect the LiDAR data. The point density is about 2 – 4 points/m^2. Aerial digital orthophoto maps with a resolution of 0.2 m, which were produced during 2015 – 2016, were collected from the Guangxi administration of surveying and geographic information. In addition, high resolution satellite images of 2017 – 2019, such as GF-1/2, ZY-2 and other, were collected and processed.

Meanwhile, field plots were measured and a stratified random sampling scheme was used. 100 plots were measured for each forest species group, which are eucalypt, Chinese fir, pine and other broadleaves. Each plot is 600 m^2 (20 m×30 m). Each plot was divided into 4 subplots with 10 m×15 m. All trees with a DBH over 5 cm were measured, recording DBH and species. Tree height and crown radius were measured for 3 trees at each stand with an average DBH level and 2 dominating trees in each subplot, which accounts for 20 trees for each plot. The Differential Global Positioning System (DGPS) was used to measure two diagonal coordinates with submeter accuracy. Lorey's height was calculated as stand mean height. The stand volume density was calculated using basal area and mean height.

Aerial photos were used to determine stand boundaries manually. Photo interpretation and hyperspectral image classification were used to determine forest species group (Figure 9.4). The LiDAR-derived matrix was calculated for each plot. Linear regression was used to estimate stand variables (height, basal area, volume density, stem density, canopy closure). The indices include percentile height and corresponding density, vertical stratified height and corresponding density, and other statistical variables. A stepwise method was used to select contributing variables. Then these selected variables were calculated for all LiDAR data with a cell size of 20 m×20 m.

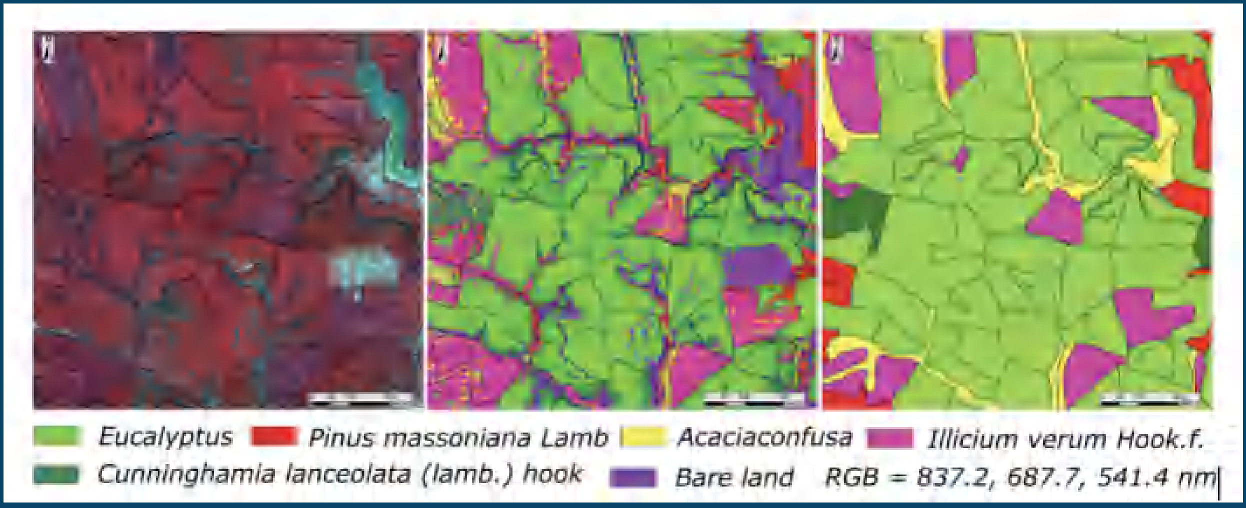


FIGURE 9.4: Forest hyperspectral image determine forest species group and stand boundaries

Source: IFRIT, CAF
Note: The figure on the left is a forest stand sub-compartment overlaid on an airborne hyperspectral image. The 2nd image from the left shows the species classification result using airborne hyperspectral image based on a support vector machine (SVM) classifier. Training samples were extracted by photo interpreted species group information shown in 3rd left image and field data.

METHODOLOGY FOR CALCULATING ABOVE-GROUND FOREST CARBON

In order to estimate forest above-ground carbon storage, the project used the biomass expansion factor (BEF) of different forest types to convert timber volume to biomass. BEF varies with forest age, site class, stand density, and other biotic and abiotic factors that are closely associated with relative stand density, and can be expressed as a function of timber volume. In this project, forest above-ground carbon for each forest type in Nanning region was calculated based on stand volume, BEF functions, and relative parameters.

FOREST STAND VOLUME MAP

The project area covers more than 2 million hm^2. The forest stand polygons were digitized based on aerial photos with 0.5 m spatial resolution. Forest type information was also interpreted by local foresters using these aerial photos. Five classes were used to stratify forest parameter estimation models, which include Chinese fir, pine, eucalypts, broadleaved forest, and shrub forest. Forest attributes, such as DBH, height, basal area, canopy cover, and stand volume were predicted and mapped in a grid of 30 m×20 m by a multi-power model developed through LiDAR-derived metrics and field measurement data.

All the forest inventory attributes were validated through select sampling of sub-compartments and determined to be accurate. The overall accuracies are 92% for mean height and 90.7% for volume density. Figure 9.5 shows the stand volume map of Gaofeng forest farm, Shangsi county and Hengxian county respectively.

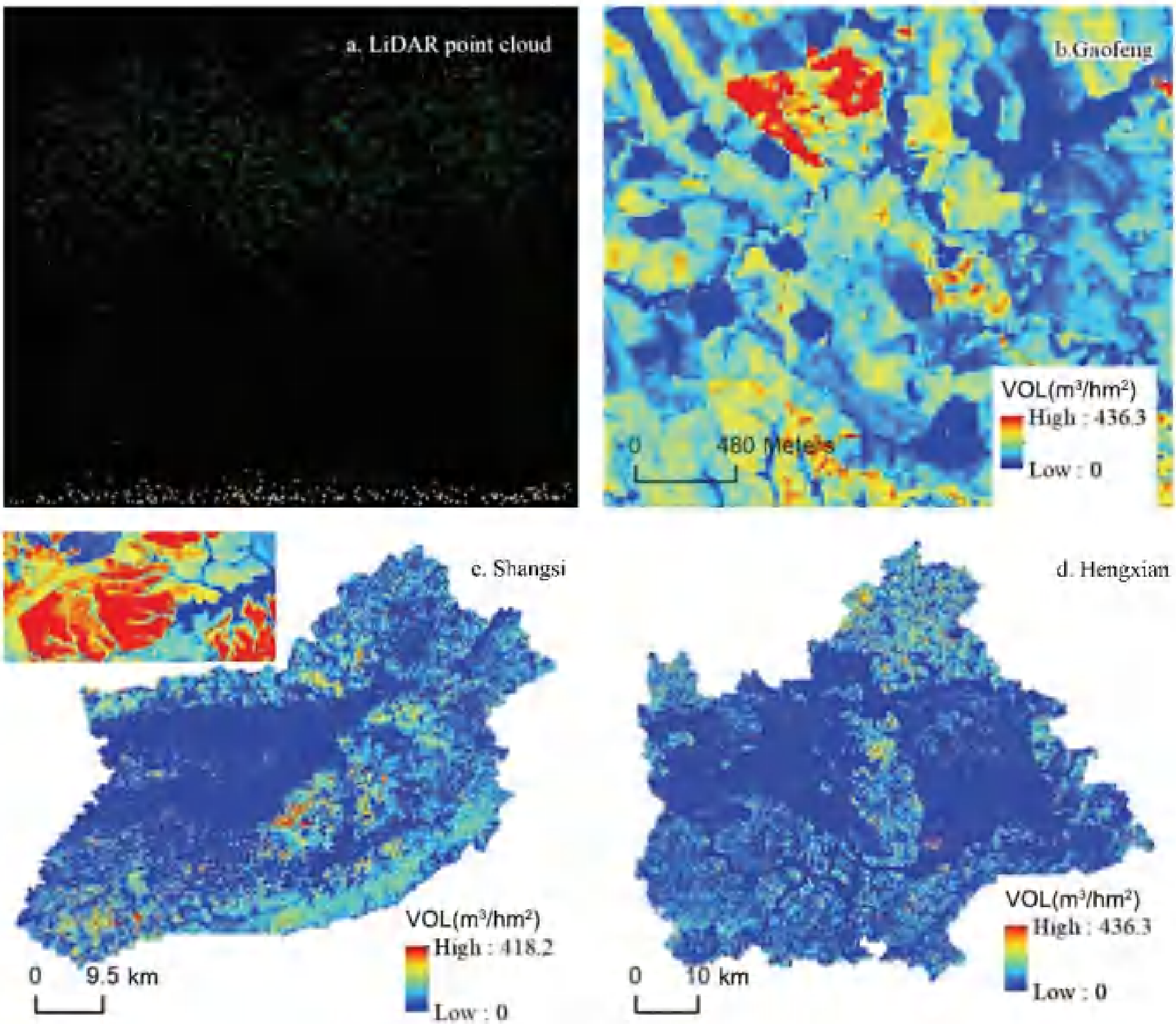


FIGURE 9.5 : LiDAR point cloud vertical distribution on plot level with a resolution of 30 m×20 m (a) and a thematic map of stand volume in Gaofeng forest farm (b), Shangsi County (c) and Hengxian County (d) in 2017

Source: GFIRI, China

FOREST HEIGHT AND VOLUME DENSITY MODELING RESULTS

Five indicators were used for assessing the performance of forest height and volume density modeling (Table 9.1, Figure 9.6-9.8), including the determination correlation (r^2), the Root Mean Square Error (RMSE), the Standard Error of Estimate (SEE), the Maximum Permissible Error (MPE), and the Maximum Permissible Square Error (MPSE).

TABLE 9.1: Forest height (H) and volume density (V) modeling results between field measurements and LiDAR matrix

Forest type and variable	Plot no.	r^2	RMSE	SEE	MPE	MPSE
Chinese fir V	89	0.80	21.1	20.93	4.89	16.51
Pine V	95	0.87	17.3	23.29	5.99	15.09
Eucalyptus V	106	0.82	17.1	18.29	5.62	9.89
Other broadleaf V	98	0.80	19.0	21.35	10.09	32.07
Lorey's H	388	0.90	1.2	1.21	4.13	7.99

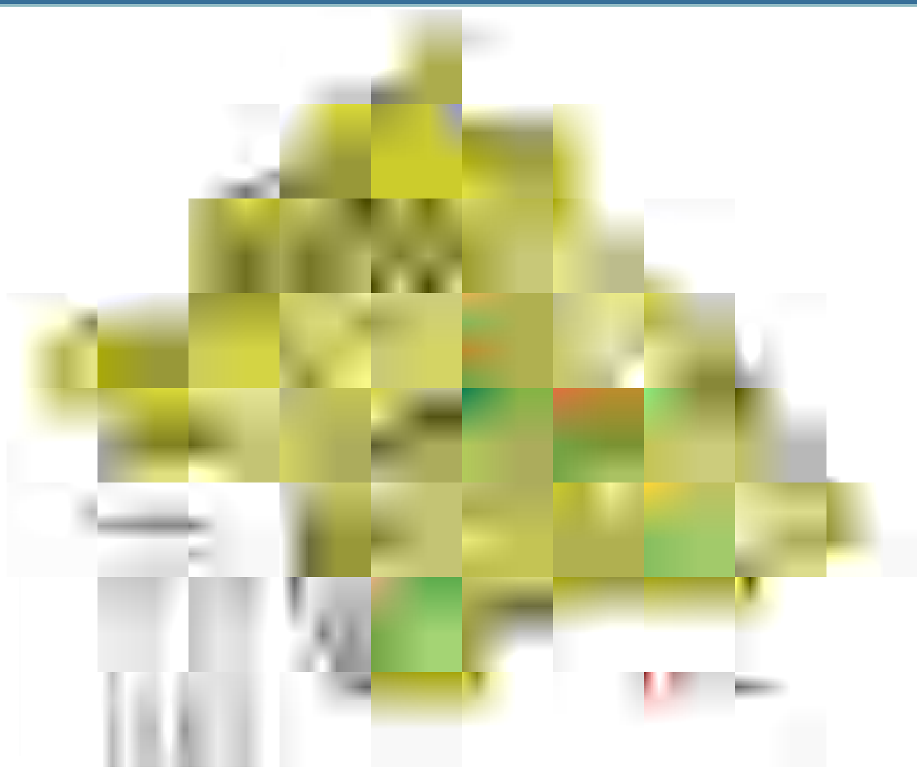


FIGURE 9.6 : Thematic map of stand mean height around Nanning region in 2017

Source: GFIRI, China

FIGURE 9.7: Thematic map of stand volume density in Nanning region in 2017

Source: GFIRI, China

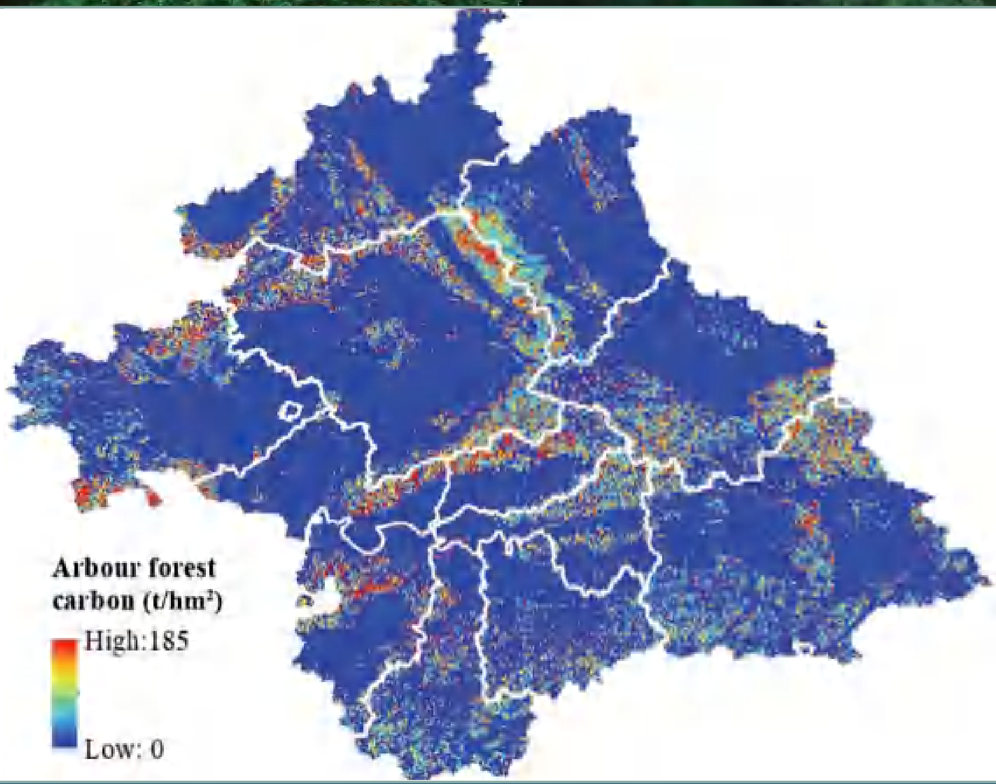
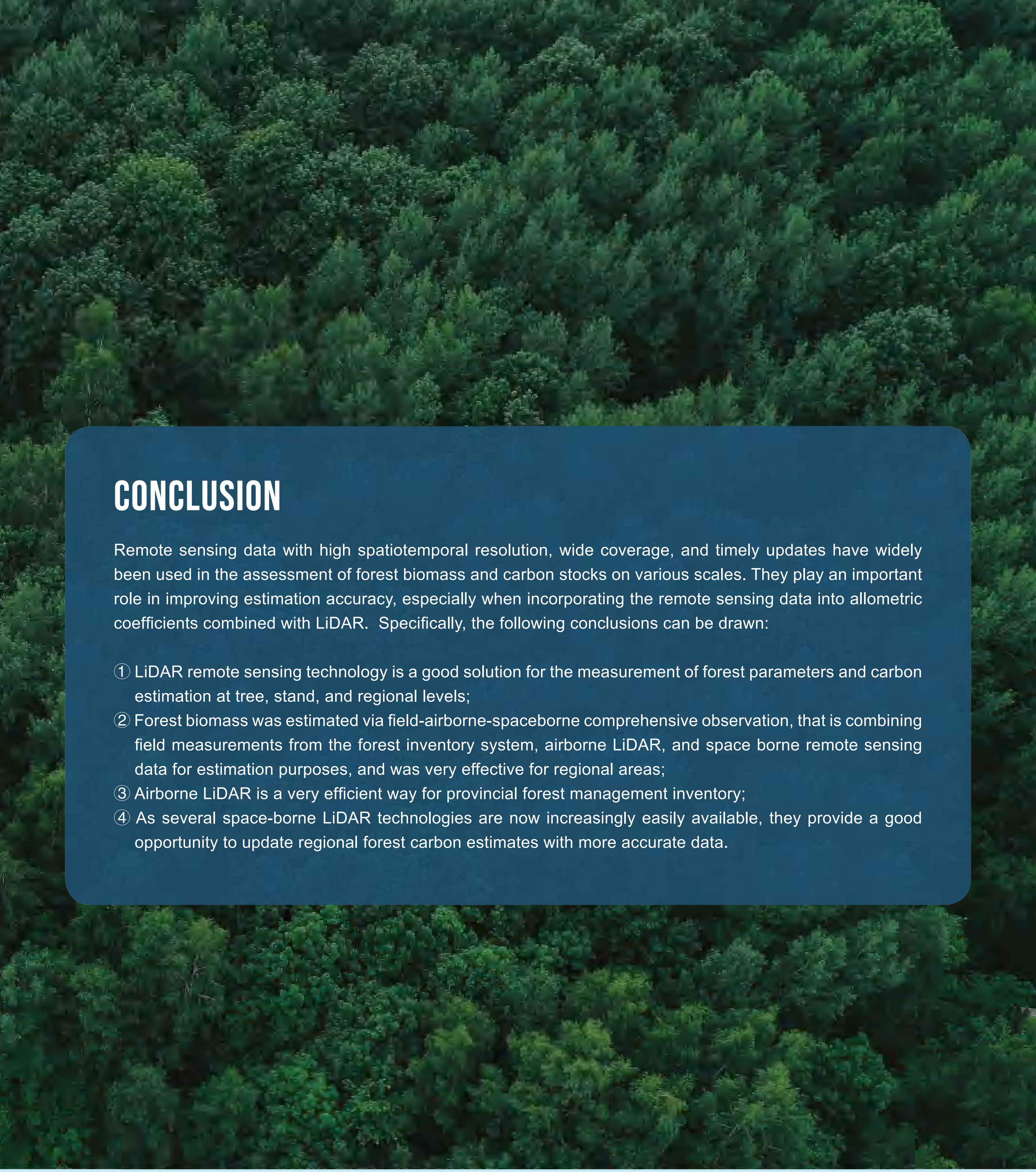


FIGURE 9.8: Forest carbon in Nanning region

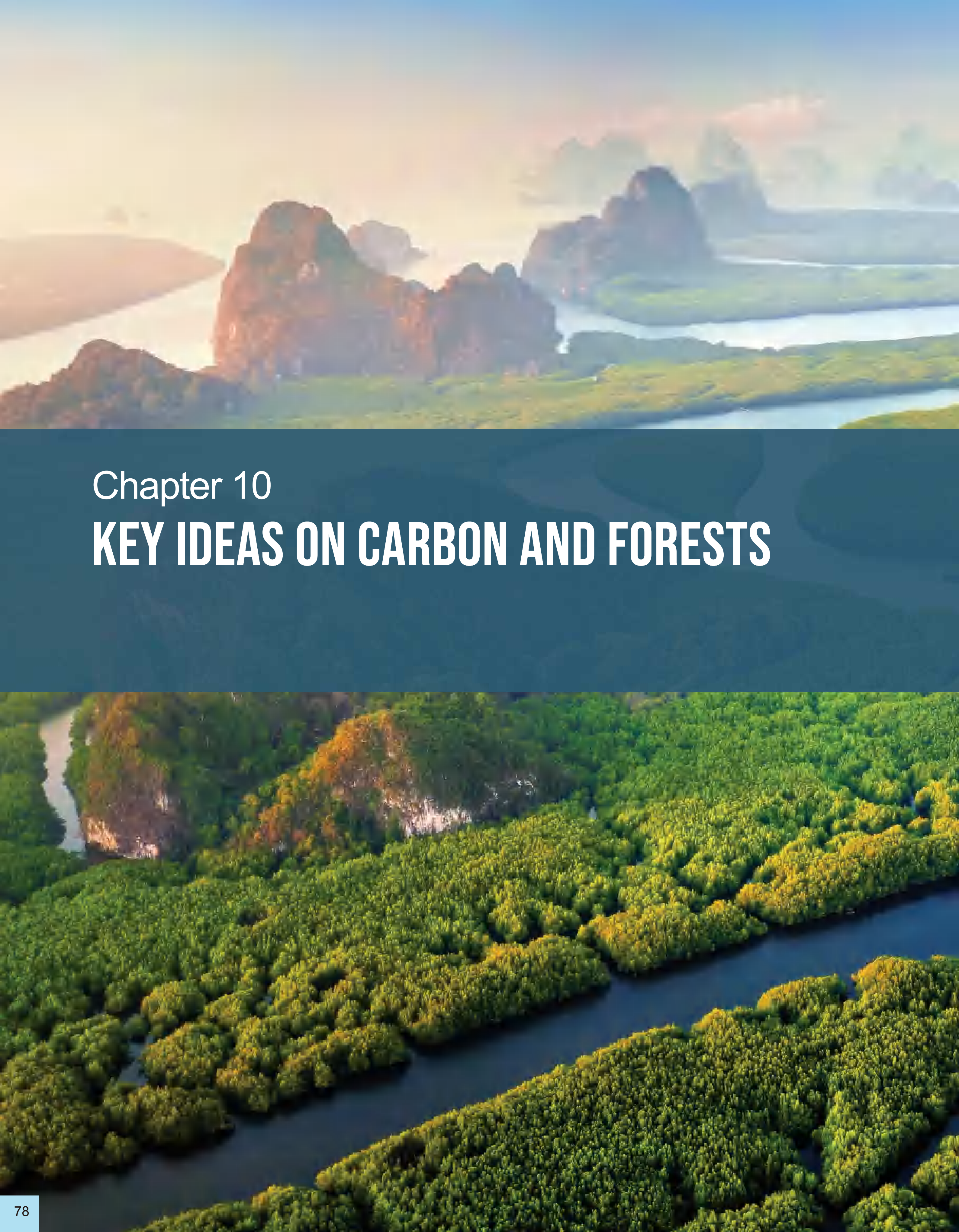
Source: GFIRI, China



CONCLUSION

Remote sensing data with high spatiotemporal resolution, wide coverage, and timely updates have widely been used in the assessment of forest biomass and carbon stocks on various scales. They play an important role in improving estimation accuracy, especially when incorporating the remote sensing data into allometric coefficients combined with LiDAR. Specifically, the following conclusions can be drawn:

① LiDAR remote sensing technology is a good solution for the measurement of forest parameters and carbon estimation at tree, stand, and regional levels;
② Forest biomass was estimated via field-airborne-spaceborne comprehensive observation, that is combining field measurements from the forest inventory system, airborne LiDAR, and space borne remote sensing data for estimation purposes, and was very effective for regional areas;
③ Airborne LiDAR is a very efficient way for provincial forest management inventory;
④ As several space-borne LiDAR technologies are now increasingly easily available, they provide a good opportunity to update regional forest carbon estimates with more accurate data.



Chapter 10

KEY IDEAS ON CARBON AND FORESTS

INTERNATIONAL REPORTING ON CARBON

Idea ① *Prioritizing Efforts through Tiers*

An economy should choose a most suitable methodology for carbon accounting of its different forest-related reporting from Tier 1 to 3 (refer to Chapter 2). Although adopting region-specific and high-resolution data would reduce uncertainty, these methods typically require more extensive resources for data collection. By assessing the available resources and identifying key objectives, an economy can prioritize its efforts and improve its overall estimates. As for different emissions different tiers can be chosen, an economy can “mix and match” to achieve a suitable combination, reflecting the availability of information.

Idea ② *Selecting Suitable Tiers*

Emissions calculated by different tier methods and each economy-specific accounting method is different for the same categories of carbon source (i.e. fuel combustion activities, forest fires and animal respiration) and sink (i.e. ocean, soil and forests), as the conditions and available data and methodology in the different economies can differ vastly. In general, the IPCC suggests using high (tier 2 or 3) methods. In practice, the methods used in different categories in different economies depend on whether the data collected and available is sufficient for the application of the higher tier method or whether a lower tier methodology specified in the IPCC Guidelines can sufficiently reflect accurate emissions in the category. For example, Japan, an Annex I[1] economy, reports hydrofluorocarbons (HFCs), sulfur hexafluorides (SF_6), and perfluorocarbons (PFC_s) emissions for the metal industry, which are not reported in other economies as it is difficult to obtain this type of data. Thus, for Non-Annex I[2] economies like China or the majority of APEC economies, it is suggested to rather focus on fully applying IPCC Guidelines when reporting emissions using Tier 1 parameters, for the purpose of giving continuous emissions reporting and providing completed preliminary analysis.

Idea ③ *Continuity of Reporting*

Generally, in the carbon accounting framework, once a voluntary activity is elected for a commitment period, it should remain elected in subsequent commitment periods. Once a unit of land enters the LULUCF accounting, it should remain being accounted for during that commitment period and in the future, even if no any activity is further implemented on that piece of land.

[1] *Annex I Parties include the industrialized economies that were members of the OECD (Organisation for Economic Cooperation and Development) in 1992, plus economies with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.*

[2] *Non-Annex I economies are developing economies under the Kyoto Protocol. Non-Annex I economies do not have legally binding emissions reduction targets.*

MEASURING EMISSIONS FROM PEATLAND FIRES

Idea ① *Incomplete combustion of carbon during fire events*

One fire does not combust 100% of the carbon available in a peatland forest, yet to date calculation standards are insufficient for different carbon pools. Rather, different carbon pools have to be accounted for separately in regards to peatland fire emissions. This applies especially to the idea of multiple fires, as in how much and what type of carbon pool is burned with each subsequent fire in order to report accurately about peatland fire emissions.

Idea ② *Increased carbon concentrations due to fire*

Specifically for peat, an increased number of fires can actually increase carbon concentration (but not necessarily the total amount of carbon stored), possibly as a result of pyrogenic carbon filtering and higher bulk density.

Idea ③ *Emissions from peatland fires lower than assumed*

Emissions from peatland fires in Indonesia are vastly overestimated and, based on this research, could be up to three times lower than previously assumed. This may also have implications for peatland emissions reported from other economies.

DEVELOPING STANDING-TREE CARBON EQUATIONS TO IMPROVE THE ACCURACY OF FOREST-COVER CARBON STOCK ESTIMATES

Idea ① *Representativeness of Standing-tree Carbon Equations*

Standing-tree carbon equations need to comply with certain standards of representativeness and accuracy, including a sufficient species and age range in order to be able to make accurate predictions.

Idea ② *Variability of carbon/biomass fractions in different tree species*

The carbon/biomass fraction of 0.47 provided by the IPCC is in reality highly variable from tree species to tree species, depending on wood density etc., thus equations should reflect the diversity of values.

Idea ③ *Producing carbon maps via NDVI*

Using NDVI and ground-truthing, the carbon values obtained for different forest types on different sample plots can be used to produce carbon maps and calculate overall forest carbon stock for a region via GIS.

FOREST CARBON STOCKS IN THE CONTEXT OF RESTORATION ACTIVITIES

Idea ① *Bamboo and some softwoods sequester carbon the quickest*

Fast-growing plants, such as bamboo and certain softwoods, sequester carbon the quickest in the initial reforestation period. Among all the restoration models, total carbon storage has the largest increment at the site of restoring low-yield moso bamboo plantations, amounting to 18.43 tC/hm^2. The site with the second largest increase in carbon sink is the demonstration plot of large-diameter Chinese fir, where it has an increase of $5.65t/hm^2$.

Idea ② *Selling carbon credits could improve local livelihoods*

The sale of carbon credits can significantly improve local livelihoods while promoting forest restoration if the right carbon accounting methodology is set up. The project has established a valuable methodology as it accounts small-scale forest carbon sink in a project level, especially in family-managed forests and cooperative-managed forests.

INVENTORY-BASED CARBON ESTIMATION AT THE FOREST MANAGEMENT UNIT LEVEL

Idea ① *Carbon estimation methods for the forest management unit level still lacking*

Aside from national or large-scale inventory-based forest carbon estimation, at the forest management unit level, efficient, accurate, workable and cost-effective carbon accounting methodologies are needed for estimating carbon stocked in forest ecosystems.

Idea ② *Continuous BEF equations may be the best choice for forest management unit level carbon calculations*

The current given BEF or BCF are usually suitable for application on a larger scale, but will cause a big error if applied at the forest management unit level. It is suggested that continuous BEF equations for main forest types be developed, which could accurately reflect the relationship between stand volume and total vegetation biomass for certain areas.

Idea ③ *Optimizing forest management to improve carbon storage*

Forest management activities should take into consideration increasing forest carbon stocks to fulfill the forest carbon carrying capacity, so as to contribute to the carbon neutrality commitment. Optimized silviculture and forest management practices are needed, especially in plantation forests.

FOREST ABOVEGROUND CARBON DENSITY ESTIMATION USING LIDAR REMOTE SENSING TECHNOLOGY

Idea ① *Combining different methodologies to estimate forest biomass*

For regional areas, estimating forest biomass through Field-Airborne-Spaceborne (FAS), that is combining field measurements from forest inventory system, airborne LiDAR, and space borne remote sensing data for estimation purpose, was very effective. This is because field measurements could verify forest area, whereas LiDAR is able to obtain high-precision vertical structure information of forest, especially the airborne LiDAR, and the space borne remote sensing data focuses on ice and vegetation in high latitudes.

Idea ② *Importance of accurate forest type maps for large scale estimation*

Having access to accurate forest type maps and conditions is beneficial to predict the carbon stock in the forested landscapes accurately. Forest mapping is very significant for the estimation and evaluation of the forest resources, carbon stock, and to support sustainable forest management.

CARBON MARKETS & CARBON TRADE

Idea ① *Setting up carbon accounting for carbon markets*

When a methodology is developed, one should make sure that it align with international and national standards for the potential to enter carbon markets, even if this is not the primary goal of the methodology.

Idea ② *Carbon accounting costs*

Carbon accounting can be expensive. Measuring forest carbon for the trade of carbon credits might be difficult for landowners to pay off considering the current carbon price. Subsidies or other financial incentives provide an option to involve more local-level participants.

Chapter 11

CONCLUSION

As we have seen throughout this book forest ecosystems can play a significant role in combating global climate change through their capacity to sequester carbon. Forest carbon accounting enables us to measure the amount of carbon stored in a forested area or the carbon flow in or out of the forest. Knowledge derived from forest carbon accounting is a prerequisite for governments or regulators to get involved in GHG negotiations or carbon trading. As carbon markets continue to develop, there is also an opportunity to improve the livelihoods of forest-dependent populations through managing forests sustainably and selling forest carbon credits.

When stakeholders, either the state, institutions, or individuals, decide to measure the carbon of a site, they should first identify the objectives and goals of the carbon accounting and determine whether the primary purpose is for national reporting, carbon trading, or other, both in the long and short term. They should also consider whether they are interested in measuring carbon sinks, emissions, or emission reductions. These objectives determine which international guidelines or national guidelines the stakeholders should follow. Then they should identify the forest type and the scale of their site, which impacts the methodology applied. Stakeholders should also identify existing methodologies and available data and pair them with the resources and expertise they have to prioritize the most suitable methodology.

This book introduced the context of forest carbon accounting and five APFNet projects that provided useful case studies. These APFNet projects span across different climates and forest types, such as peatland, broad-leaved or coniferous mixed forest in different economies. Some of these were the first forest carbon accounting projects in the region, including the project in Inner Mongolia and the

project in Anhui and Zhejiang of China, while others have improved on existing national carbon reporting, such as the projects in Indonesia and in Thailand. These examples showcase various methodologies applicable in the Asia-Pacific region and allow practitioners to identify the methodologies most suitable to their own sites.

However, it is also critical to realize that some of these projects only established pilots for carbon accounting and collected only preliminary data that needs to be scaled up. Meanwhile, the accumulation of massive research data provides the basis for subsequent research work. Some challenges remain. For example, conducting carbon accounting is very costly, while the price of carbon in the carbon market is relatively low. Thus, many entities have little motivation to measure carbon in their properties. Additionally, analyzing forest carbon of a region requires long-term observation of forest ecosystem changes, yet forest inventories in some of the poorer Asia-Pacific economies is absent, sporadic or poorly conducted.

We hope that through this book relevant officials and professionals are not only provided with new, interesting methodologies, but are also encouraged to continue to put their efforts and resources behind carbon accounting to both increase the total amount of data available, but also its quality. APFNet, as a leading international organization in the Asia-Pacific region, is committed to continue to support and demonstrate the best forest carbon accounting practices and help enhance forest carbon stocks in the region. Just as titled in the book we are aiming to “Hold Forests Accountable” both now and in the future.

REFERENCES

APEC, 2007. Sydney APEC Leader's Declaration on Climate Change, Energy Security and Clean Development[R/OL] . Asia-Pacific Economic Cooperation[2022-3-21] : https: //www. apec. org/meeting-papers/leaders-declarations/2007/2007_aelm/aelm_climatechange

BIRD D. N., PENA N., SCHWAIGER H. et al., 2010. Front Matter. In Review of existing methods for carbon accounting(pp. i–ii)[R/OL] . Center for International Forestry Research[2022-1-5] http: //www. jstor. org/stable/resrep02196. 1

BROWN S., 1997. Estimating Biomass and Biomass Change of Tropical Forests: a Primer[C/OL] . FAO Forestry Paper134: 1-4[2022-3-12] . http: //www. fao. org/docrep/w4095e/w4095e00. htm.

CHEN JM, JU WM, CIHLAR J, et al. 2003. Spatial distribution of carbon sources and sinks in Canada's forests[J] . Tellus. 55B: 622-641.

CHEN J., BRAUCH M. D., 2021. Comparison Between the IPCC Reporting Framework and Country Practice[R] . Columbia: The Columbia Center on Sustainable Investment.

DAHY B., ISSA S., KSIKSI T., et al., 2020. Geospatial Technology Methods for Carbon Stock Assessment: A Comprehensive Review[J] . In IOP Conference Series: Earth and Environmental Science, 540(1): 012036.

EG-GLESTON H., BUENDIA L., MIWA K., et al., 2006. IPCC Guidelines for National Greenhouse Gas Inventories[R] . In IPCC. Institute for Global Environmental Strategies.

FANG J., CHEN, A. PENG, C., ZHAO S., et al., 2001. Changes in Forest Biomass Carbon Storage in China Between 1949 and 1998[J] . Science, 292(5525): 2320-2322.

FAO, 2012. Peatlands-Guidance for Climate Change Mitigation Through Conservation, Rehabilitation and Sustainable Use (2nd Edition)[R] . Rome: Food and Agriculture Organization of the United Nations.

FAO, 2019. From reference levels to results reporting: REDD+ under the United Nations Framework Convention on Climate Change[R] . Rome: Food and Agriculture Organization of the United Nations.

GRISCOM B. W., ADAMS J., ELLIS P. W., et al., 2017. Natural climate solutions[J] . Proceedings of the National Academy of Sciences, 114(44): 11645-11650.

GWENZI D., LEFSKY M. A., 2014. Modeling canopy height in a savanna ecosystem using spacebome lidar waveforms[J] . Remote Sens. Environ. 154: 338-344.

MARRAKECH PARTNERSHIP, 2021. Climate Action Pathway: Land Use Vision and Summary 2021[R/OL] . Global Climate Action, United Nations Climate Change[2021-11-2] . https: //unfccc. int/sites/default/files/resource/Vision%26Summary_Landuse. pdf.

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems[R] . Geneva: Intergovernmental Panel on Climate Change.

Indonesia, 2016. First Nationally Determined Contribution[R] .

IPCC, 2003. Good practice guidelines for land use, land-use change and forestry[R] . Geneva: International Panel on Climate Change. Japan: IGES.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories[R] . Geneva: International Panel on Climate Change. Japan: IGES .

IUCN, 2021. IUCN Issues Brief – Forests and Climate Change[R/OL] . Gland: International Union for Conservation of Nature[2021-12-25] . https: //www. iucn. org/resources/issues- briefs/forests-and-climate-change.

IVERSEN P., LEE D., ROCHA M., 2014. Understanding land use in the UNFCCC[EB/OL] . [2021-11-10] .] https: //ghginstitute. org/ wp-content/uploads/2015/04/Understanding_Land_Use_in_the_UNFCCC. pdf.

KASETSART UNIVERSITY, 2018a. Development of Standing Tree Carbon Equations (To Demonstrate the Development and Application of Standing-Tree Carbon Equations to Improve the Accuracy of Forest-Cover Carbon Stock Estimates in Thailand - Technical Report 1)[R/OL] . Beijing: APFNet[2021-10-3] . https: //www. apfnet. cn/plus/view. php?aid=4318.

KASETSART UNIVERSITY, 2018b. Application of Standing-Tree Carbon Equations: Preparation of Carbon Stock Maps (To Demonstrate the Development and Application of Standing-Tree Carbon Equations to Improve the Accuracy of Forest Cover Carbon Stock Estimates in Thailand - Technical Report 2)[R/OL] . Beijing: APFNet[2021-10-3] https: //www. apfnet. cn/plus/view. php?aid=4318.

KRISNAWATI H., ADINUGROHO W. C., IMANUDDIN R., et al., 2021. Carbon balance of tropical peat forests at different fire history and implications for carbon emissions[J/OL] . Science of the Total Environment, 779: 146365[2022-1-7] . https: //doi. org/10. 1016/j. scitotenv. 2021. 146365.

KRUG J. H. A., 2018. Accounting of GHG emissions and removals from forest management: A long road from Kyoto to Paris[J/OL] . Carbon Balance and Management, 13(1): 1-11[2021-11-14] . https: // doi. org/10. 1186/s13021-017-0089-6.

LENG L. Y., AHMED O. H., JALLOH M. B., 2019. Brief review on climate change and tropical peatlands[J/OL] . Geoscience Frontiers, 10(2): 373–380[2021-11-20] . https: //doi. org/10. 1016/j. gsf. 2017. 12. 018.

LI X., LIU Z., LIN H., et al., 2020. Estimating the Growing Stem Volume of Chinese Pine and Larch Plantations based on Fused Optical Data Using an Improved Variable Screening Method and Stacking Algorithm[J/OL] . Remote Sensing, 12(5): 871[2021-12-4] . https: //doi. org/10. 3390/rs12050871.

LI Z., XIAO J., LU G., et al., 2020. Productivity and profitability of *Larix principis-rupprechtii* and *Pinus tabuliformis* plantation forests in Northeast China[J/OL] . Forest Policy and Economics, 121(9): 102314[2022-1-12] . https: //doi. org/10. 1016/j. forpol. 2020. 102314.

MATTHEWS G., 1993. The carbon content of trees[Z] . Forestry Commission Technical Paper: 4.

MOEF, 2016. National Forest Reference Emission Level for Deforestation and Forest Degradation: in the Context of Decision 1/CP[R] . 16 para 70 UNFCCC (Encourages developing country Parties to contribute to mitigation actions in forest sector): Post Technical Assessment.

PAGE S. E., RIELEY J. O., BANKS C. J., 2011. Global and regional importance of the tropical peatland carbon pool[J/OL] . Global Change Biology, 17(2): 798–818[2021-12-25] . https: //doi. org/10. 1111/j. 1365-2486. 2010. 02279. x.

PAN Y., BIRDSEY R. A., FANG J., et al., 2011. A large and persistent carbon sink in the world's forests[J] . science, 333(6045): 988-993.

SANTIN C., DOERR S. H., JONES M. W., et al., 2020. The Relevance of Pyrogenic Carbon for Carbon Budgets From Fires: Insights From the FIREX Experiment[J/OL] . Global Biogeochemical Cycles, 34(9): 0-3[2022-2-15] . https: // doi. org/10. 1029/2020GB006647.

SHAO W., CAI J., WU H., et al., 2017. An Assessment of Carbon Storage in China's Arboreal Forests[J/OL] . Forests 2017, 8(4): 110[2021-10-23] . https: //doi. org/10. 3390/F8040110.

SHI L., LIU S., et al., 2017. Methods of Estimating Forest Biomass: A Review[M/OL] //Biomass Volume Estimation and Valorization for Energy, February[2021-10-5] . https: //doi. org/10. 5772/65733.

SIAHAAN H., KUNARSO A., SUMADI A., et al., 2020. Carbon lossaffected by fires on various forests and land types in south sumatra[J/OL] . Indonesian Journal of Forestry Research, 7(1): 15–25[2022-3-10] . https: // doi. org/10. 20886/ijfr. 2020. 7. 1. 15-25

TANG X., ZHAO X., BAI Y., et al., 2018. Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey[J/OL] . Proceedings of the National Academy of Sciences of the United States of America, 115(16): 4021–4026[2021-11-12] . https: //doi. org/10. 1073/PNAS. 1700291115/-/DCSUPPLEMENTAL.

UN News, 2021. China headed towards carbon neutrality by 2060;President Xi Jinping vows to halt new coal plants Abroad[N/OL] . [2022-1-21] . https: //news. un. org/en/story/2021/09/1100642.

UNFCCC, 1998. The Kyoto Protocol[Z] . New York: General Assembly of the United Nations.

UNFCCC, 2014. Handbook on Measurement, Reporting and Verification for developing country parties[M] . New York: United Nations Climate Change Secretariat.

UNFCCC, 2018. China. Biennual update report (BUR)[R/OL] . New York: General Assembly of the United Nations, BUR 2[2021-12-28] . Retrieved from: https: //unfccc. int/sites/default/files/resource/China%202BUR_English. pdf.

UNFCCC, 2020. Thailand's Updated Nationally Determined Contribution[EB/OL] . General Assembly of the United Nations[2022-1-2] . https: //www4. unfccc. int/sites/ ndcstaging/PublishedDocuments/Thailand%20First/Thailand%20Updated%20NDC. pdf.

UNFCCC, 2021. What is the United Nations Framework Convention on Climate Change?[R/OL] General Assembly of the United Nations[2022-1-19] . https: //unfccc. int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change.

VETRITA Y., COCHRANE M. A., 2020. Fire frequency and related land-use and land-cover changes in Indonesia's Peatlands[J/OL] . Remote Sensing, 12(1)[2021-12-10] . https: //doi. org/10. 3390/RS12010005.

VOLKOVA L., KRISNAWATI H., ADINUGROHO W. C., et al., 2021. Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires[J/OL] . Science of the Total Environment, 763: 142933[2022-3-1] . https: //doi. org/10. 1016/j. scitotenv. 2020. 142933.

WANG G., OYANA ., ZHANG M., et al., 2009. Mapping and spatial uncertainty analysis of forest vegetation carbon by combining national forest inventory data and satellite images[J] . Forest Ecology and Management, 258: 1275-1283.

WATSON C., 2009. Forest carbon accounting: overview and principles[J] . Forest Carbon Accounting Overview & Principles.

WHITTAKER R. H., 1963. Net Production of Heath Balds and Forest Heaths in the Great Smoky Mountains[J/OL] . Ecology, 44(1): 176-182[2021-10-21] . https: //doi. org/10. 2307/1933200.

XIANG Y., TAO R., WAN L., et al., 2020. OS-PC: Combining feature representation and 3-D phase correlation for subpixel optical and SAR image registration[J] . IEEE Transactions on Geoscience and Remote Sensing, 58(9): 6451-6466.

XU K. J., TIAN Q. J., YUE J. B., et al., 2018. Forest tree species identification and its response to spatial scale based on multispectral and multi-resolution remotely sensed data[J/OL] . Chinese Journal of Applied Ecology, 29(12): 3986–3994[2022-1-21] . https: // doi. org/10. 13287/j. 1001-9332. 201812. 011.

YAN F., GONG Y., FENG Z., 2015. Combination of artificial neural network with multispectral remote sensing data as applied in site quality evaluation in Inner Mongolia[J/OL] . Croatian Journal of Forest Engineering, 36(2): 307-319[2021-11-21] . http: //www. crojfe. com/archive/volume-36-no. 2/combination-of-artificial-neural-network-with-multispectral-remote-sensing-data -as-applied-in-site-quality-evaluation-in-inner-m/.

YANAI R. D., WAYSON C., LEE D., et a., 2020. Improving uncertainty in forest carbon accounting for REDD+ mitigation efforts[J/OL] . Environmental Research Letters, 15(12): 124002[2021-12-10] . https: //doi. org/10. 1088/1748-9326/ABB96F.

ZENG W., FORESTRY N., 2018. Comparison of Different Methods for Estimating Forest Biomass and Carbon Storage Based on National Forest Inventory Data May[J/OL] . Forest Research, 2018, 31(1): 66-71[2021-10-5] . https: //doi. org/10. 13275/cnki. lykxyj. 2017.

ZHAO K. G., POPESCU S., NELSON R., 2009. Lidar remote sensing of forest biomass: a scale-invariant estimation approach using airborne lasers[J] . Remote Sens. Environ. 113: 182-196.

Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)

Address: 6th Floor, Baoneng Center (Building A), 12 Futong Dongdajie, Chaoyang District Beijing, 100102, P.R. China

Website: www.apfnet.cn

Contact: Zhang Shiyi, Project Manager (zhangshiyi@apfnet.cn)

ISBN 978-7-5219-1999-8
9 787521 919998 >
Price：CNY68.00