Carbon Stocks and Carbon Footprint of Bamboo Timber Products

竹材产品碳储量与碳足迹研究

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科学出版社

浙江省重点科技创新团队“林业碳汇与计量”项目资助(2010R50030)
科技部“十二五”国家科技支撑计划项目资助(2012BAD22B05)
浙江大庄实业集团有限公司资助
浙江省森林生态系统碳循环与固碳减排重点实验室成果
浙江省农民发展研究中心成果

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内 容 简 介

木竹材产品碳库是森林三大碳库之一，已被纳入森林减排范畴。我国竹林资源和竹材产品产量均位居世界第一，竹材产品碳储量和碳足迹的研究，对深化竹林全生命周期碳汇功能的科学评估、了解区域和国家水平上森林碳汇的贡献具有重要意义。全书基于对浙江、福建、江西、四川4省100多家竹材产品生产企业的实地调查，选取了1000多株6～16cm胸径分布的伐后毛竹，全程跟踪计测竹材产品生产每道工艺前后的碳转移率，构建了毛竹不同胸径、不同生产技术下竹材产品碳转移率和碳储量模型，为准确地估算竹材产品碳储量提供了科学方法和技术支撑；结合竹材产品碳储量，精准计测了5类9种主要竹材产品的碳足迹，为衡量竹材产品的低碳程度提供了依据；最后从直接减排和间接减排角度提出了增加碳储量、降低碳足迹的建议。

本书适用于对林业与气候变化、碳排放核算、产品碳足迹、低碳社会发展等热点问题关注的广大科研工作者、相关政府部门人员、企业人员、相关专业研究生和本科生阅读。

图书在版编目（CIP）数据

竹材产品碳储量与碳足迹研究 / 周国模，顾蕾著．—北京：科学出版社，2017.3

ISBN 978-7-03-051152-2

I.①竹…　II.①周…　②顾…　III.①竹制品-加工-二氧化碳-排放-研究　IV.①TS959.2

中国版本图书馆CIP数据核字（2016）第317477号

责任编辑：张会格　闫小敏 / 责任校对：郑金红
责任印制：张　伟 / 整体设计：铭轩堂

科学出版社 出版
北京东黄城根北街16号
邮政编码：100717
http://www.sciencep.com

北京教图印刷有限公司印刷
科学出版社发行　各地新华书店经销

*

2017年3月第　一　版　开本：720×1000　B5
2017年3月第一次印刷　印张：10 7/8
字数：219 000

定价：78.00元

前　言

增加森林碳汇已成为我国政府应对气体变化、缓解减排压力的重要战略选择。造林再造林、减少毁林、促进森林可持续经营等森林增汇策略均已在应对气候变化的相关政治和法律框架中得到了体现，具有很大的减排潜力和明显的成本优势。但一直以来，全球对森林碳汇贡献的评估主要着眼于森林生态系统中的生物量和土壤碳储量上，而忽略了森林采伐后转移储存所形成的巨大林产品碳库。木竹材产品碳库是森林三大碳库之一，在减缓碳排放上具有巨大的贡献。2011 年在南非德班召开的联合国气候变化大会缔约方第 17 次会议上，各国一致同意将林产品碳储量纳入森林减排范畴。

竹子属禾本科竹亚科植物，广泛分布于亚洲、南美洲和非洲地区。全球约有 150 属 1225 种，据联合国粮食与农业组织（FAO）（2010 年）统计，全球竹林面积为 3185 万 hm^2，是世界第二大森林资源。我国地处世界竹子分布的中心，竹子资源十分丰富，主要分布于浙江、福建、江西等 15 个省区，约占世界竹种的 40% 和竹林面积的 20%，竹林资源和竹材产品产量均位居世界第一。根据第 8 次全国森林资源清查结果显示，我国竹林面积共 601 万 hm^2，2014 年竹业总产值达 1845 亿元，竹产业已成为我国林业“十三五”期间重点发展的十大主导产业之一和农民家庭收入的主要来源。

研究表明，竹林生态系统具有高效的固碳能力，并且成林后可隔年择伐。由于加工利用技术的提高和竹材产品种类丰富，以竹代木的趋势更加显著，因此竹林碳汇不断向竹材产品碳库转移，是一个不可忽视的重要碳库；同时在低碳产品认证的背景下，这类包含碳存储的竹材产品，碳足迹有多大，低碳程度如何，都是亟待解决的课题。因此系统开展竹材产品碳转移与碳足迹研究，对深化竹林全生命周期碳汇功能的科学评估，努力研究提高产品碳储量、降低产品碳足迹的技术，实现我国“森林增汇”的目标及帮助企业应对碳关税贸易壁垒、提高竹材产品竞争力都具有重要的意义。

浙江农林大学林业碳汇与计量科技创新团队从 2001 年起开始了竹林碳汇的

研究，主要集中在竹林生态系统的生物量碳和土壤碳两方面。为了全面评估竹林全生命周期碳汇功能，必须了解伐后竹材产品碳储量和碳足迹方面的特征和规律。作者历经8年的潜心研究，实地调查了浙江、福建、江西、四川4省100多家竹材产品生产企业，选择了1000多株6～16cm胸径分布的伐后毛竹，开展了对5种有代表性的竹材产品（集成板材、重组板材、刨切板材、展开板材、拉丝材）和3种主要的生产技术（集成技术、重组技术、展开技术）的研究，基于企业生产单位的微观视角，全程跟踪、计测产品生产每道工艺前后的碳转移率，研究不同胸径、不同生产技术对竹材产品碳转移率和碳储量的影响；基于上述研究最终选择了5类9种最终竹材产品[带青竹展开地板、去青竹展开砧板（两种规格）、竹重组地板（户外和室内）、竹刨切片、竹拉丝产品（竹窗帘、竹凉席、竹地毯）]，开展了碳足迹及其影响因素研究，研究取得以下突破。

第一，从研究方法上突破了竹材产品碳转移、碳储量计测中尺度与精度共融的难题，提出基于企业微观角度，通过跟踪竹材产品生产工艺流程，分析碳转移规律和特征，构建碳储量计测模型，实现了宏观尺度和微观方法的结合，解决了竹材产品“如何测碳”的技术难题。

第二，根据整株毛竹不同胸径和壁厚分段利用的特点，通过分段再整合整株碳转移率，揭示了竹材产品碳转移规律，构建了不同胸径毛竹的整株碳转移率和碳储量模型，为快速精确地估算伐后不同胸径毛竹碳转移量提供了理论基础，结合毛竹胸径的Weibull分布概率模型，可准确计测任意区域尺度的伐后毛竹转移到竹材产品的碳储量，解决了竹材产品“固碳多少”的科学问题。

第三，系统研究了我国目前主要竹材产品（板材类、拉丝类、刨切类）及生产技术（集成、重组、展开、拉丝）的碳转移率，建立了不同产品类型、不同生产技术的碳转移率和碳储量模型，为高度精准、普遍适用地估算不同类型的竹材产品碳储量提供了科学的方法，解决了竹材产品“固碳途径”的科学问题。

第四，基于竹材产品B2B（business-to-business）生命周期，全程跟踪并系统测定9种主要竹材产品在生产过程中的碳排放，结合碳储量数据科学测算了产品碳足迹，首次精准衡量了竹材产品的低碳程度，为确定竹材产品的低碳属性提供了依据，并分析了竹材产品的减排潜力，提出了降低碳足迹的对策，为企业减排及应对碳贸易壁垒提供了科学方法和依据，解决了竹材产品“固碳贡献”的科学问题。

将以上研究成果著成《竹材产品碳储量与碳足迹研究》一书，以全新的视

角向读者介绍了伐后毛竹的碳转移轨迹、碳储量大小及产品低碳程度，完善了竹林全生命周期碳汇功能的科学评估，并为“竹子造林碳汇项目方法学”和“竹子经营碳汇项目方法学”提供了伐后竹林碳转移、碳储量计测的技术支撑。

全书共分两部分16章，各部分、章节的研究内容和结论如下。

第一部分为竹材产品碳储量研究，分为8章。

第1章，系统梳理和分析了国内外木竹材产品碳储量的研究背景、现状和未来趋势，阐述了目前国内外木竹材产品碳储量的研究方法和内容。

第2章，论述了竹材产品碳储量的研究思路、内容和方法，提出了基于企业生产单位微观视角，全程跟踪、计测产品生产每道工艺前后的碳转移率，研究不同胸径、不同生产技术对竹材产品碳转移率和碳储量的影响。

第3～6章，根据毛竹材分段利用的特点，分别计测了使用不同生产技术（集成技术、重组技术、展开技术）后整株毛竹竹板材的碳转移率和碳储量大小，构建了不同生产技术下不同胸径竹板材的碳储量模型。毛竹展开板材碳转移率及碳储量最高，毛竹重组板材次之，毛竹刨切板材最低。

第7章，研究了毛竹分段中拉丝段（壁厚在5～9 mm）的碳转移率和碳储量。拉丝材最终加工成竹席丝、竹帘丝、竹筷条等束状材料。根据计测，不同胸径毛竹拉丝材的原竹段综合碳转移率平均为32.51%。

第8章，对上述5种竹材产品在3种生产技术下的碳转移率和碳储量进行了比较分析和系统梳理，并从竹林培育、生产技术、工艺、全竹利用、废料再循环利用角度提出了增加竹材产品碳储量的建议。

第二部分为竹材产品的碳足迹研究，分为8章。

第9章，系统梳理和分析了国内外碳足迹的研究背景、现状和未来趋势，阐述了目前国内外碳足迹的研究方法和内容。

第10章，论述了竹材产品碳足迹的研究思路、内容和方法，应用英国标准协会（BSI）PAS 2050：2008《产品碳足迹评价规范》，基于第一部分竹材产品的碳储量结果和使用寿命，系统核算不同生产技术下主要耐用竹材产品的碳足迹。

第11～15章，选择了5类9种最终竹材产品进行碳足迹评估，涵盖了目前竹材产品生产的3种主要技术：集成技术、重组技术、展开技术。通过计测不同竹材产品从原材料到最终产品入库（B2B）所有排放源的初级活动水平数据，着重对产品加工过程、运输过程和附加物的排放等重点排放源进行计测，结合

碳排放因子数据和全球增温潜势，对竹材产品 B2B 生命周期的二氧化碳排放量作出准确核算，并结合竹材产品的碳储量和使用寿命对竹材产品的碳足迹（净排放）进行精确评估，进一步分析了各种竹材产品的碳足迹构成。根据计测得到：①从各类竹材产品碳排放的构成来看，运输过程化石能源排放、加工过程电力排放、附加物隐含排放为最主要的三大排放源，而其中加工过程电力排放在竹材产品碳排放中所占比例最大。②从 9 种竹材产品每立方米储存的碳储量效应来看，其主要受转移储存的碳储量多少和产品使用寿命影响，最终竹重组地板（户外）最大，竹展开砧板（规格 2）最小。③从 9 种竹材产品每立方米最终的碳足迹来看，综合上述碳排放和碳储量效应，最终带青竹展开地板碳足迹最小，竹刨切片最大。

第 16 章，总结了 9 种竹材产品碳足迹评估中存在的不确定性因素，并基于生命周期评价法、投入产出分析法和层次分析法，从影响产品碳排放及碳足迹的 5 个层次进行了减排潜力分析，最终从直接减排和间接减排两条途径提出降低碳足迹的建议。

在本书相关内容研究过程中，得到了浙江大庄实业集团有限公司及其福建顺昌、福建建阳、江西资溪子公司，浙江省安吉县林业局、临安市林业局、龙泉市林业局、庆元县林业局、遂昌县林业局，四川省长宁县林业局、青神县林业局及其竹材产品生产企业等企事业单位的大力支持；浙江农林大学周宇峰、施拥军、郑国全、刘恩斌、李翠琴、徐小军等老师参与了研究方案的设计和实施；研究生陈艳艳、毛方杰、俞淑红、计露萍、彭伟亮、周鹏飞、李想、李翀等在外业调查、数据分析和书稿文字、图表整理等方面做了大量的工作，在此一并表示感谢。

作为我国首部系统阐述竹材产品碳储量和碳足迹计测的专著，本书科学的研究方法和创新的研究成果可为研究其他木材产品碳储量和碳足迹提供重要的参考和借鉴。限于著者水平，书中存在一些不足之处，恳请广大读者批评指正。

著　者

2016 年 6 月

Preface

Increasing forest carbon sequestration serves as an important strategic choice for the Chinese government to combat climate change and mitigate the pressures from emission reductions measures. A number of strategies for increasing forest carbon sequestration, such as afforestation, reforestation, deforestation reduction and the promotion of sustainable forest management, are reflected in relevant political and legal frameworks designed to combat climate change demonstrating great potential in reducing emissions and noticeable cost advantages. However, globally, the focus when assessing the contribution to forest carbon sequestration has always been on the biomass and soil carbon stocks of forest ecosystems, ignoring the immense forest product carbon pool generated from carbon transfers and storage after the logging of forests. The forest product carbon pool, one of the three major forest carbon pools, contributes tremendously to the mitigation of carbon emissions. At the 17th United Nations Framework Convention on Climate Change Conference of the Parties held in Durban, South Africa, in 2011, all countries unanimously agreed to include forest product carbon stocks in the realm of forest carbon emission reductions.

Bamboos, a plant subfamily (*Bambusoideae*) in the family *Poaceae*, are widely distributed throughout Asia, South America and Africa. Globally, there are approximately 150 bamboo genera and 1225 bamboo species. Bamboo forests, comprising an area of 22 million ha, are the second largest forest resources in the world. Geographically located in the middle of the world's distribution of bamboo species, China has abundant bamboo resources, which are primarily distributed in 15 provinces and regions, including Zhejiang, Fujian and Jiangxi etc. China accounts for approximately 40% of the global bamboo species and 20% of the bamboo forest area. In addition, China has the largest bamboo forest resources and highest bamboo product yield in the world. According to the results of the Eighth National Forest Inventory, China's bamboo forest area totaled 6.01 million ha and the bamboo industry in China had a total output value of 184.5 billion Chinese yuan in 2014. The bamboo industry, currently one of the ten major leading forest industries, the development of which was prioritized during China's 13th Five-Year Plan period, serves as a primary source of income for rural families.

Research has shown that bamboo forest ecosystems have highly efficient carbon sequestration capacity; in addition, a bamboo forest, once established, can also be subjected to selective logging every other year. Given improved techniques for processing and using bamboo, the types of bamboo products are increasingly more diverse and the trend of replacing wood with bamboo is progressively more pronounced. As a result, the focus of bamboo forest carbon sequestration continuously shifts to the creation of bamboo product carbon pools, which are important carbon pools that should not be overlooked. In addition, low-carbon product certification is also gaining momentum. Accordingly, the carbon footprint and low-carbon levels of bamboo products that store carbon need to be promptly determined. Therefore, systematic research on the carbon transfer and carbon footprint of bamboo products is of great importance to further develop scientific assessments of the carbon sequestration function of bamboo forests throughout their entire life cycle, to advance research on the techniques for increasing product carbon stocks and reducing product carbon footprints, to achieve the Chinese government's goal of increasing forest carbon sequestration and to strengthen the capacity of companies to combat carbon tariff trade barriers and increase the competitiveness of their bamboo products.

Since 2001, the team at Zhejiang A & F University responsible for innovating forest carbon sequestration and calculation and measurement technologies has been studying bamboo forest carbon sequestration, primarily focusing on two areas—the biomass carbon and soil carbon of bamboo forest ecosystems. To comprehensively assess the carbon sequestration function of a bamboo forest during its full life cycle, it is necessary to understand the characteristics and patterns of the carbon stock and carbon footprint of harvested bamboo products. During eight years of concentrated research, we conducted field surveys on more than 100 bamboo product manufacturing companies in four Chinese provinces (Zhejiang, Fujian, Jiangxi and Sichuan), selecting more than 1000 harvested Moso bamboo plants with a diameter at breast height (DBH) distributed in the range of 6–16 cm for analysis, and investigated five representative bamboo products (laminated bamboo boards, reconstituted bamboo boards, sliced bamboo veneers, flattened bamboo boards and drawn bamboo threads) and three representative production techniques (lamination, reconstitution and flattening). In addition, from the micro-level, we also surveyed all the companies' bamboo product manufacturing processes, calculated and measured the carbon transfer ratio of each production process, and studied the effect of different DBHs and production techniques on the carbon transfer ratio obtained when producing bamboo products as well as the bamboo product carbon stock. Based on the aforementioned investigations, we eventually selected nine types of final bamboo products belonging to five categories (flattened green-barked bamboo flooring boards, flattened bamboo cutting boards (two specifications), reconstituted bamboo flooring boards (outdoor and indoor), sliced bamboo veneers and drawn bamboo thread products (bamboo curtains, bamboo mats and bamboo carpets) to study bamboo product carbon footprints and the factors affecting them. We achieved the following developments.

First, we resolved the difficulty in simultaneously ensuring adequate scale and accuracy when calculating and measuring bamboo product carbon transfer and carbon stocks by using a new research method. At the micro-level, by surveying the bamboo product manufacturing processes, we analyzed the carbon transfer pattern and characteristics involved in producing bamboo products and constructed a carbon stock calculation and measurement model, thereby achieving a combination of macro- and micro-scale methods and thus solving the technical difficulty in measuring the carbon-related parameters of bamboo products.

Second, considering that the DBH and wall thickness of a Moso bamboo plant vary between different sections of the plant and a Moso bamboo plant is thus first divided into different sections prior to use, we first divided a bamboo plant into different sections and then combined the carbon transfer ratios obtained when producing bamboo products using each of the bamboo sections to obtain the carbon transfer ratio of the entire plant, thereby revealing the carbon transfer pattern when producing bamboo products. In addition, we also established a model for determining the carbon transfer ratio and carbon stock of entire bamboo plants with different DBHs, thereby providing a theoretical basis for rapidly and accurately estimating the amount of carbon transferred from harvested Moso bamboo plants with different DBHs. The proposed model, combined with the Weibull distribution probability model of the DBH of Moso bamboo plants, can be used to accurately calculate and measure the amount of carbon transferred from harvested Moso bamboo plants to bamboo products in any area on any scale, thereby solving the scientific problem of determining the amount of carbon sequestrated by bamboo products.

Third, we systematically studied the carbon transfer ratio obtained when producing the chief bamboo products (bamboo board products, drawn bamboo thread products and sliced bamboo veneers) using the predominate bamboo product production techniques (lamination, reconstitution, flattening and drawing) currently practiced in China. We also established carbon transfer ratio and carbon stock models for different product types produced using different production techniques, thereby providing a scientific method for accurately and ubiquitously estimating the carbon stock of different types of bamboo products and solving the scientific problem of determining the carbon sequestration pathway of bamboo products.

Fourth, based on the business-to-business (B2B) life cycle of bamboo products, we surveyed the entire manufacturing process of nine types of bamboo products and systematically measured the carbon emissions generated during each production process. Based on the carbon stock data, we scientifically measured and calculated product carbon footprints and, for the first time, accurately assessed the low-carbon level of bamboo products, thereby providing a basis for determining the low-carbon attributes of bamboo products. In addition, we also analyzed the potential of reducing the carbon emissions generated during the production of bamboo products and proposed strategies for reducing bamboo product carbon footprints, providing companies with a scientific method and basis for reducing carbon emissions and combating carbon trade barriers, thereby solving the scientific problem of determining the contribution of bamboo products to carbon sequestration.

Based on the aforementioned research results, we have developed this book, entitled *A Study on Bamboo Product Carbon Stocks and Carbon Footprints*, which introduces to the reader the carbon transfer trajectory and carbon stock of harvested Moso bamboo plants, as well as the low-carbon level of Moso bamboo products, from a novel perspective and improves the scientific assessment of the carbon sequestration function of bamboo forests during their complete life cycle. In addition, this book also provides technical support for the *Methodology for Carbon Sequestration through Bamboo Afforestation* and the *Methodology for Carbon Sequestration through forest Management* in the areas of calculating and measuring the amount of carbon transferred from and the carbon stock of harvested bamboo forests.

This book has two parts and 16 chapters. The research contents and conclusions of each part and chapter are as follows:

Part 1, consisting of eight chapters, discusses bamboo product carbon stocks.

Chapter 1 systematically organizes and analyzes the background, current situation and future trend of worldwide research on bamboo product carbon stocks, as well as discusses the methods and contents of current worldwide research on bamboo product carbon stocks.

Chapter 2 discusses the ideas, contents and methods of research on bamboo product carbon stocks, proposes a method for calculating and measuring the carbon transfer ratio of each bamboo product manufacturing process by following all the production processes at the micro-level of companies, and details our investigation of the effect of different DBHs and production techniques on the carbon transfer ratio obtained when producing bamboo products and the bamboo product carbon stock.

Chapters 3–6 calculate and measure the carbon transfer ratio of entire Moso bamboo plants when used to produce bamboo products using different production techniques (lamination, reconstitution and flattening) and the carbon stock of different types of bamboo boards based on how Moso bamboo plants are used (a Moso bamboo plant is divided into different sections prior to use) and establish carbon stock models for bamboo boards produced from bamboo plants with different DBHs using different production techniques. The carbon transfer ratio is the highest when producing flattened Moso bamboo boards from Moso bamboo plants, followed by reconstituted Moso bamboo boards and sliced Moso bamboo veneers. In addition, flattened Moso bamboo boards also have the highest carbon stock, followed by reconstituted Moso bamboo boards and sliced Moso bamboo veneers.

Chapter 7 investigates the carbon transfer ratio obtained when producing drawn bamboo threads from the suitable sections of Moso bamboo plants (wall thickness: 5–9 mm) as well as the carbon stock of drawn bamboo thread products. Drawn bamboo threads are eventually processed into bundle-like materials such as bamboo mat threads, bamboo curtain threads and bamboo chopstick rods. Based on calculations and measurements, the mean combined carbon transfer ratio is 32.51% when producing drawn bamboo threads.

Chapter 8 comparatively analyzes and systematically organizes the carbon transfer ratios obtained when producing the aforementioned five types of bamboo products using three production techniques and the carbon stock of these bamboo products, as well as provides suggestions on how to increase bamboo product carbon stocks through bamboo forest cultivation, production techniques, processes, the use of entire bamboo plants and bamboo scrap recycling.

Part 2, consisting of Chapters 9–16, details the research on bamboo product carbon footprints.

Chapter 9 systematically organizes and analyzes the background, current situation and future trend of worldwide research on carbon footprints and discusses the current methods and contents of worldwide research on carbon footprints.

Chapter 10 discusses the ideas, contents and methods of research on bamboo product carbon footprints and systematically calculates the carbon footprint of the main durable bamboo products manufactured using different production techniques based on the results of the carbon stock and service life of bamboo products obtained in Part 1 using the British Standards Institution's Product Carbon Footprint Assessment Standard (PAS2050： 2008).

Chapters 11–15 assess the carbon footprint of nine types of final bamboo products belonging to five different categories. The selected bamboo products are produced using three primary production techniques that are currently used to produce bamboo products, namely, lamination, reconstitution and flattening. Carbon dioxide emissions generated during the B2B life cycle of bamboo products are accurately calculated by measuring the primary activity level data of all the emission sources involved in each step of manufacturing different bamboo products (from the raw materials to the warehousing of the final products), with a focus on measuring the data of major emission sources involved during the product processing and transportation processes, as well as the data of emissions embodied in the additives, based on carbon emission factor data and global warming potential. In addition, bamboo product carbon footprints (net emissions) are also accurately assessed based on their carbon stock and service life, and the composition of the carbon footprint of each type of bamboo products is further analyzed. The following conclusions are obtained based on the calculations and measurements： ①In terms of the composition of the carbon footprint of each type of bamboo product, carbon emissions are primarily generated from three main types of sources： fossil energy sources during the transportation process, power sources during the processing process and additives (in which carbon emissions are embodied). Of the three main types of emission sources, carbon emissions from power sources during the processing process account for the majority of all carbon emissions. ② The carbon stock stored in each of the nine types of bamboo products per m^3 is primarily affected by the amount of carbon transferred when manufacturing the product and the service life of the product. Reconstituted bamboo flooring boards (for outdoor applications) have the highest carbon stock per m^3, and flattened bamboo cutting boards (specification 2) have the lowest carbon stock per m^3. ③ In terms of the final carbon footprint per m^3 of the nine types of bamboo products, based on the aforementioned carbon emission and carbon stock data, flattened green-barked bamboo flooring boards have the smallest carbon footprint and sliced bamboo veneers have the largest carbon footprint.

Chapter 16 summarizes the uncertainty factors existing in the assessment of the carbon footprint of the nine types of bamboo products; analyzes the potential of reducing carbon emissions in five areas that affect product carbon emissions and carbon footprints based on the life cycle assessment method, the input–output analysis method and the analytic hierarchy process; and, lastly, proposes suggestions on how to reduce the carbon footprint via two different approaches, direct and indirect carbon emission reduction approaches.

During our research, we received strong support from a number of enterprises and institutions, including Zhejiang Dasso Industrial Group Co., Ltd. and its subsidiary companies in Fuchang and Jianyang, Fujian Province and Zixi, Jiangxi Province, Anji County Forestry Bureau of Zhejiang Province, Lin'an City Forestry Bureau of Zhejiang Province, Longquan City Forestry Bureau of Zhejiang Province, Qingyuan County Forestry Bureau of Zhejiang Province, Suichang County Forestry Bureau of Zhejiang Province, Changning County Forestry Bureau of Sichuan Province, Qingshen Country Forestry Bureau of Sichuan Province and the bamboo product manufacturers in Qingshen County, Sichuan Province. We wish to thank Prof. Zhou Yufeng, Prof. Shi Yongjun, Prof. Zheng Guoquan, Prof. Liu Enbin, Prof. Li Cuiqin and Prof. Xu Xiaojun from Zhejiang A & F University for their participation in the design and implementation of the research plan and graduate students Chen Yanyan, Mao Fangjie, Yu Shuhong, Ji Luping, Peng Weiliang, Zhou Pengfei, Li Xiang and Li Chong for their extensive work in field investigation, data analysis and manuscript, chart and figure preparation.

This book is the first publication that systematically elucidates the calculation and measurement of bamboo product carbon stocks and footprints published in China. The scientific research methods and novel research results detailed in this book can provide an important reference for research on the carbon stocks and footprints of other types of wood products. Because of our limited capacity, we may have overlooked some important information and made errors and omissions in this book. Hence, we earnestly welcome your criticism and correction.

The authors

June 2016

目　录

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