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Contributions of China's Wood-Based Panels to CO_2 Emission and Removal Implied by the Energy Consumption Standards

Shanshan Wang [1,2], Han Zhang [2,3], Ying Nie [2,4] and Hongqiang Yang [1,2,5,*]

1 Department of Economics and Management, Nanjing Forestry University, No. 159, Longpan Road, Nanjing 210037, Jiangsu, China; wssnjfu@outlook.com
2 Research Center for Economics and Trade in Forest Products of the State Forestry Administration (SINO-RCETFOR), No. 159, Longpan Road, Nanjing 210037, Jiangsu, China; hanzhang@nwafu.edu.cn (H.Z.); ynieh@njfu.edu.cn (Y.N.)
3 Department of Economics and Management, Northwest A&F University, No. 3, Taicheng Road, Yangling 712100, Shanxi, China
4 Business College, Jinling Institute of Technology, Nanjing 210037, Jiangsu, China
5 Center for the Yangtze River Delta's Socioeconomic Development, Nanjing University, No. 22, Hankou Road, Nanjing 210093, Jiangsu, China
* Correspondence: yhqnfu@gmail.com; Tel.: +86-25-8542-7378

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Abstract: Life cycle analysis on wood-based panels in terms of CO_2 flux can be used to quantitatively assess the climate change contributions of these materials. In this study, the annual CO_2 flux between 1990 and 2015 was calculated through gate-to-gate life cycle analysis of wood-based panels. As implied by the energy consumption standards, China's wood-based panels used to be carbon sources during the period 1990–2007, with the average contribution to CO_2 emissions of 9.20 Mt/year. The implementation of new standards and the development of Cleaner production technologies in China, decreased the energy consumption per panel. China's wood-based panels acted as a carbon sink between 2008 and 2015, with the average contribution to CO_2 removal of 31.71 Mt/year. Plywood produced the largest contributions to the emission and removal of CO_2, and was followed by fiberboard and particleboard. China's wood-based panels, with good prospects and strong demands projected in the future, can potentially contribute to climate change mitigation.

Keywords: wood-based panels; climate change mitigation; energy consumption; production approach

1. Introduction

The ongoing international concern for climate change has obtained increased attention from developing countries due to their rapidly growing greenhouse gas (GHG) emissions [1]. China has committed to a 40%–45% reduction in GHG emissions per unit of gross domestic product (GDP) by 2020 compared with 2005 and has planned to peak in carbon emission reduction by around 2030 [2]. The growing concern over the impacts of climate change has emphasized the mitigation potential of forests and forest-derived products, specifically in terms of carbon sequestration [3]. The use of wood and wood-based products exerts positive effects on the environment, such as mitigating climate change or reducing waste and other emissions [4].

The wood-based panel industry is an important forest-based one in China. The country is the largest wood-based panel producer worldwide, with a total output of 286.80 million m^3 in 2015 [5]. The main panels, namely, plywood, fiberboard, and particleboard account for 87.85% of China's wood-based panel industry. Among wood-based panels, plywood dominates with 57.69% of production and is followed by fiberboard at 23.08% of the total output. The yield of particleboard accounts for 7.08% of the total output [5]. Due to the high economic importance of wood-based panels in China, the production has expanded considerably in recent years and is expected to increase with an average annual growth rate of 1.05% from 2015 to 2030 [6]. On the one hand, the carbon storage in wood-based panels has increased annually due to an increase in net primary production [7,8]. On the other hand, gate-to-gate product manufacturing consumes various energy sources, and almost all energy consumption results in GHG emissions [9].

The major GHG is CO_2 with less contribution from CH_4 and N_2O [10]. The contributions of wood-based panels include the contributions to annual CO_2 emissions and removals [11]. Direct emission occurs during production, whereas indirect emission is associated with purchased electricity and product end-of-life. Other emission types are associated with fiber and non-fiber productions, transportation, and product use [12]. In compensating for CO_2 emissions, the net removal contributions are obtained on the basis of the estimation of CO_2 stocks [13].

Several studies have focused on environmental impact assessments on wood-based panels. These studies compared the environmental influence of plywood, fiberboard, and particleboard to address issues of global warming, acidification, eutrophication, dust, wastes, and resource consumption [14]. Syahirah [15] compared the environmental impacts of panel preparation, shaping, and finishing on the wood-based industry in Malaysia. The growing focus on carbon as an indicator of environmental performance [16] has encouraged studies on carbon flux through the processing stages, carbon stored in products, and carbon footprint for on-site manufacture and cradle-to-product gate processes. Wilson [10,17] and Sakimoto [18] calculated the carbon footprints of production of American particleboard, medium-density fiberboard, and softwood plywood, using the Simapro 7.1 software (Pre'Consultants, Amersfoort, The Netherlands) and assessed the CO_2 fluxes of these materials through the carbon content in the products. Garcia and Freire [19] compared three different tools for assessing environmental impact of particleboard and showed that treating biogenic CO_2 causes the main difference in global warming and greatly benefits global warming. In 2012, Bergman et al. [20] quantified environmental impact using the life cycle assessment method on five wood-based panel products made in North America.

The literature review shows that stored carbon per unit of wood-based panels can offset the carbon emissions from on-site manufacturing and is better than climate-neutral materials with a carbon store equal to their carbon emissions. Some studies have only estimated carbon storage of the national wood-based panel pool and its mitigation potential [21,22]. Few studies have comprehensively assessed the contributions of national wood-based panels to CO_2 emissions or removals. Less attention has been attached to GHG contributions to the atmosphere. Current research in China is restricted to carbon footprint or carbon stock calculations per volume of fiberboard and particleboard [23,24].

The climate change contributions should be assessed and the environmental profile of wood-based panels should be improved in China to meet its GHG emission reduction targets. This work focused on the environmental impact of CO_2 emission or removal. CO_2 flux can be used to comprehensively assess the actual effects of products on climate change within their entire life cycle [25]. This work derived the annual CO_2 fluxes through the life cycle of wood-based panels to determine their role in climate change between 1990 and 2015.

2. Methodology and Data

2.1. System Dynamic Structure and Functional Unit

The first step in calculating CO_2 flux is to determine the system boundary of wood-based carbon flow, which uses two major system boundaries [26]. One is the cradle-to-grave system boundary, which consists of five phases, namely, raw material extraction, product production, packaging and transportation, product use, and waste disposal [27]. As illustrated by the flow diagram in Figure 1, the cradle-to-grave analysis applied in the life cycle of harvested wood product (HWP) assesses various environmental impacts over the entire product life cycle, from raw material extraction (the cradle), via production, transportation and use, to waste management (the grave) [28]. Wood-based carbon stocks are divided into many sub-fluxes passing through various pools and processes before being released into the atmosphere [29]. The other is the gate-to-gate system boundary, which consists of two phases, namely, product manufacture and use [20,30].

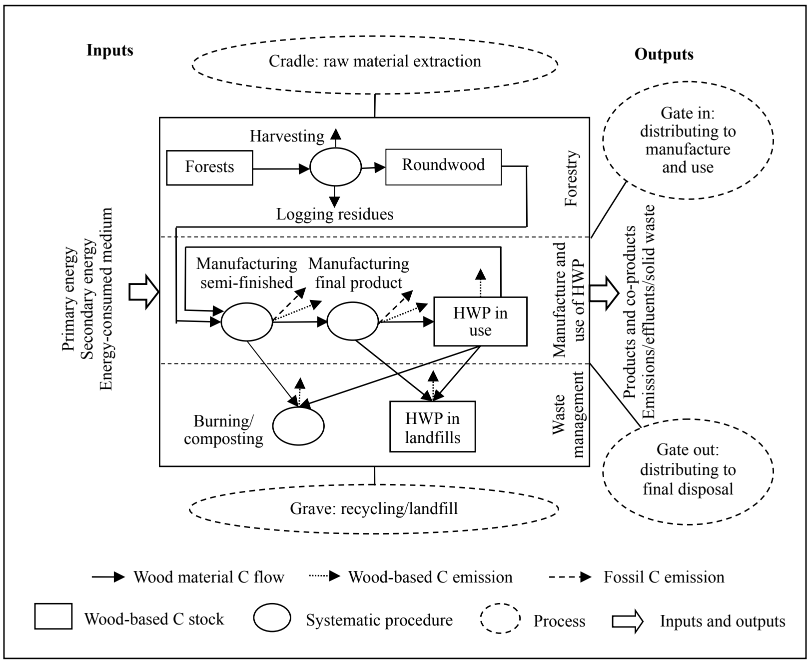

Figure 1. Wood-based carbon flow through the cradle-to-grave life cycle of harvested wood product (HWP).

For our analysis, the gate-to-gate system boundary was used (Figure 2). Forest trimmings and industrial waste wood from sawmills, such as shavings, sawdust, ply trim, veneer, and chips, are sources of raw wood materials. Plywood mostly uses large-diameter timbers as raw materials. Fiberboard and particleboard mostly use small-diameter timbers and wood residues (i.e., harvesting, building, and processing residues) from sawmills and other wood industries as major raw materials. Moreover, bark from logs and sawdust may be used to produce wood-based panels [31].

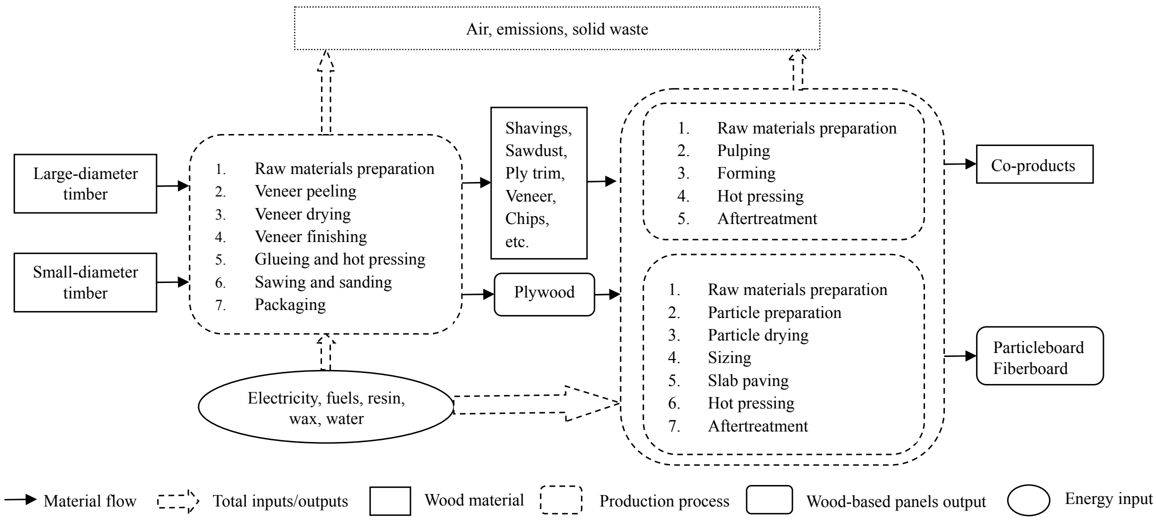

Figure 2. Gate-to-gate life cycle and process chain of wood-based panels.

Plywood production involves raw material preparation; peeling, drying, and veneer finishing; gluing and hot processing; sawing and sanding; and packaging. Carbon emission primarily occurs during gluing [32]. Fiberboard production includes raw material preparation, pulping, forming, hot processing, and after-treatment. Pulping and forming consume much energy during production [33]. Particleboard production comprises raw material preparation, particle preparation, particle drying, particle sizing, slab paving, hot pressing, and after-treatment. The energy is primarily consumed through particle preparation, drying, slab paving, and hot pressing, which account for 87.46% of the total energy consumption [34]. The three panels are produced by coordinating various procedures, which also produce pollutants and GHGs.

Using the atmospheric carbon flow as the evaluation objective, IPCC [35] stipulates that direct and indirect CO_2 emissions are positive GHG contributors and that carbon stock and substitution emission reduction are negative GHG contributors. The equation for CO_2 flux is given by:

$$CF = CE - CS \tag{1}$$

where CF, CE and CS represent the values of CO_2 flux, CO_2 emission, and CO_2 stock, respectively. If the value is above zero, then the product is a net emitter. Otherwise, the product is a net sink. CO_2 emission reduction is stipulated as a negative value [36]. The capability of carbon sinking depends on the absolute value. A high absolute value indicates increased contribution to CO_2 removal from the atmosphere [25].

The functional unit describes the quantitative measure of the functions that a product or service provides [37]. In this study, the investigated products were wood-based panels. The 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (The 2013 IPCC Guidelines) [11] stipulates that wood-based panels are reported in cubic meters (m^3) solid volume, a functional unit used in previous wood-based panel studies [10,38,39]. Therefore, the volumetric unit (m^3) was adopted as the reference in the current work to compare the gate-to-gate life cycle CO_2 flux among different panels.

2.2. CO_2 Emission and Energy Consumption Standard

This work calculated the CO_2 emissions from the production process in accordance with energy consumption standards. The overall energy consumption standards of wood-based panel production are China's forestry industry standards issued by State Forestry Administration of the People's Republic of China. These standards are recommended standards and define the relevant terms of on-site manufacture of wood-based panels and the indexes of energy consumption for producing 1 m^3 of panels. q_1 represents the specific value of the indexes and is given in kgce/m^3. Through the investigation of typical wood-based panel enterprises in China, the energy consumption of different types of enterprises was obtained. Surveyed enterprises accounted for more than 20% of the entire industry, and more than 50% of the total output was investigated. The energy consumptions per unit production of enterprises with an annual production of 50,000 m^3 of plywood and 0.2 million m^3 of particleboard were taken as the basic values [40–42], on which the different levels of indexes were based. The index values of different grades can represent the actual energy consumption of Chinese wood-based panel enterprises. The amounts of energy consumption in the entire production system were summed up and converted into standard coal [32–34]. Energy consumptions are divided into three levels in accordance with the standards, and the specific meaning of each level is as follows.

The third and qualified grades represent the limit values of energy consumption per unit product and are mandatory indicators. The purpose of these grades is to eliminate the backward production capacity of 20%–30%. The second and good grades represent the threshold values of energy consumption per unit product and are mandatory indicators. They are admittance values for production of per unit value of energy consumption for new construction, reconstruction, and expansion of enterprises. The first and excellent grades represent the advanced values of energy consumption per unit product and are recommended indicators. The numerical values indicated by the indexes are in line with the international advanced levels or the leading domestic levels for production of wood-based panels and are the goals of enterprises for on-site manufacture. Energy consumption standards are the principles that enterprises should follow in producing wood-based panels. The enterprises should calculate the energy consumption of the actual production process and match them to the grade in the standards. The comprehensive energy consumption per unit output of an enterprise in actual production refers to the ratio of total energy consumption to qualified output in the same statistical period.

Tables 1 and 2 show the different indexes according to the energy consumption standards between 1990 and 2015. The different levels of indexes were used to judge the actual production level of wood-based panel industry and service as a reference for the government to supervise the consumption of energy for production. The quantitative management of resource consumption by the state may urge enterprises to examine the energy consumption in each production process in accordance with the energy consumption levels and to reduce waste of resources. The backward production capacity that fails to meet the third and qualified grades will be eliminated [43]. The implementation of the total energy consumption standards of the wood-based panel industry in China occurs in two stages. The first stage includes LY/T 1529–1999 Total Energy Consumption in Plywood Production (LY/T 1529–1999), LY/T 1451–1999 Comprehensive Energy Consumption for Hard Fiberboard Production on the Wet Process (LY/T 1451–1999), and LY/T 1530–1999 Total Energy Consumption in Particleboard Production (LY/T 1530–1999), which were released in 1989 and implemented in 1990 [32–34].

In the first stage, the four major producers of Chinese wood-based panels are Linyi, Shandong Province; Pizhou, Jiangsu Province; Jiashan, Zhejian Province; and Wen'an, Hebei Province. Among these producers, three are located in the northern provinces (The Technical Requirements of Cleaner Production for the Wood-based Panel Industry in China defines the southern and northern provinces as the area with heating facilities and the area without heating facilities, respectively.) (i.e., Linyi, Pizhou, and Wen'an), and the total output and market share of wood-based panels of Shandong, Jiangsu, and Hebei provinces account for more than 80% of the national share. This work selected the northern provinces as regional indicators.

Table 1. Indexes of energy consumption for producing 1 m^3 of panels in the first stage (kgce/m^3).

Wood-Based Panels	Indexes	Areas	
		Southern Provinces	Northern Provinces
Plywood	First grade	$320 < q_1 \leq 450$	$420 < q_1 \leq 600$
	Second grade	$450 < q_1 \leq 600$	$600 < q_1 \leq 830$
	Third grade	$600 < q_1 \leq 900$	$830 < q_1 \leq 1100$
Fiberboard	First grade	$q_1 \leq 700$	$q_1 \leq 750$
	Second grade	$700 < q_1 \leq 750$	$751 < q_1 \leq 850$
Particleboard	First grade	$20 < q_1 \leq 410$	$260 < q_1 \leq 490$
	Second grade	$410 < q_1 \leq 590$	$490 < q_1 \leq 670$
	Third grade	$590 < q_1 \leq 830$	$670 < q_1 \leq 900$

Note: the arrangement is based on three standards: LY/T 1529–1999, LY/T 1451–1999, and LY/T 1530–1999. q_1 represents the actual energy consumption for on-site manufacture of 1 m^3 of wood-based panels.

In terms of first-level indexes, the average energy consumptions of plywood, fiberboard, and particleboard were 510, 750, and 375 kgce/m^3, respectively (Table 1)

The second stage (2008–2015) includes three current national standards: LY/T 1529–2012 Comprehensive Energy Consumption of Plywood Production (LY/T 1529–2012), LY/T 1451–2008 Overall Energy Consumption for Fiberboard Production (LY/T 1451–2008), and LY/T 1530–2011 Comprehensive Energy Consumption of Particleboard Production (LY/T 1530–2011) [40–42]. Replacing the previous energy consumption standards with the current ones includes the implementation of Excellent, Good, and Qualified index levels. The north and south areas are also unified in the same index. The reduction in energy consumptions for wood-based panel production is attributed to the application of cleaner production technologies. China's enterprises have been urged to adopt cleaner production technologies through the improvement of technologies and utilization of clean materials [44]. Thus, the calculations based on the "first grade" (Table 1) and "excellent grade" (Table 2) met the requirements for cleaner production in China's wood-based panel industry. According to the statistics, the energy consumption of China's advanced enterprises is 163–182 kgce/m^3, and that of most small- and medium-scale enterprises is 250 kgce/m^3 [45]. In addition, in the research of 20 representative enterprises, the energy consumption per unit of particleboard is 113.03 kgce/m^3 [46]. The values of actual practice conform to the first-level indexes. The results of related foreign literature showed that the energy consumptions for plywood production in the United States and Canada are 158.46 and 80.15 kgce/m^3 [47] and that the domestic practical conditions of China are close to advanced levels. Therefore, the index selection conforms to the current situation of the industry and the actual situation.

Table 2. Indexes of energy consumption for producing 1 m^3 of panels in the second stage (kgce/m^3).

Wood-Based Panels	Indexes	Values
Plywood	Excellent	$q_1 \leq 200$
	Good	$200 < q_1 \leq 240$
	Qualified	$240 < q_1 \leq 260$
Fiberboard	Excellent	$q_1 \leq 320$
	Good	$320 < q_1 \leq 380$
	Qualified	$380 < q_1 \leq 450$
Particleboard	Excellent	$q_1 \leq 120$
	Good	$120 < q_1 \leq 160$
	Qualified	$160 < q_1 \leq 200$

Note: the arrangement is based on three standards: LY/T 1529–2012, LY/T 1451–2008, LY/T 1530–2011.

In the second stage, the average energy consumptions for on-site manufacturing of plywood, fiberboard, and particleboard in terms of excellent-grade indexes were 200, 320, and 120 kgce/m^3, respectively.

2.3. CO_2 Stock and Calculation Model

2.3.1. IPCC Methodology

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (The 2006 IPCC Guidelines) identifies three feasible approaches to estimate and report national carbon stock changes of HWPs, namely, the stock change approach, the atmospheric flow approach, and the production approach. Following the 17th session of the Conference of the Parties, carbon accounting of HWP is confined to products in use, where the wood was derived from domestic harvest [48]. The principle is the same as the production approache (PA), a universal approach during the second commitment period of the Kyoto Protocol [49]. The current study calculated the gate-to-gate CO_2 flux in which the system boundary disregarded trade and excluded carbon in imported wood-based panels [11]. The PA was used to calculate only the carbon stock changes.

The first step is to estimate the share of domestically produced wood-based panels. Following the 2013 IPCC Guidelines, the domestic consumption of industrial roundwood was assumed equal to the feedstock used for manufacturing the wood-based panels. The fraction of industrial roundwood from domestic forests was computed on the basis of the production, import, and export of industrial roundwood in accordance with Equation (2):

$$f_{IRW}(i) = \frac{IRW_P(i) - IRW_{EX}(i)}{IRW_P(i) + IRW_{IM}(i) - IRW_{EX}(i)} \tag{2}$$

where $f_{IRW}(i)$ is the share of industrial roundwood used in the domestic wood-based panel production with respect to the total consumption of industrial roundwood in year i; $IRW_P(i)$, $IRW_{IM}(i)$ and $IRW_{EX}(i)$ represent the carbon content in the produced, imported, and exported industrial roundwood in year i, respectively.

The present work assumed that all domestic wood harvests were from sustainably managed forests; therefore, the calculation of carbon stocks did not differ among different afforestation activities. Equation (3) was used to calculate the annual fraction of wood-based panels entering the accounting framework from domestic harvest as follows:

$$\text{HWP}(i) = \text{P} \times f_{IRW}(i) \tag{3}$$

where $\text{HWP}(i)$ is the number of wood-based panels produced from domestic harvest in year (i), P is the total number of wood-based panels produced in year i.

The annual inflow and outflow for wood-based panels were estimated by applying default conversion factors and a first-order decay function, with the constant annual default decay factors proposed by the 2013 IPCC Guidelines. Changes in carbon stocks in year i were estimated in accordance with the following equations:

$$C(i+1) = e^{-k} \times C(i) + \left[\frac{\left(1-e^{-k}\right)}{k}\right] \times inflow(i) \tag{4}$$

$$\Delta\, C(i) = C(i+1) - C(i) \tag{5}$$

where $C(i)$ is the carbon stock of wood-based panels at the beginning of year i; $C(1900) = 0$; k is the first-order decay rate equal to $\frac{\ln(2)}{HL}$, where HL is the half-life of the wood-based panels; $inflow(i)$ is the inflow of wood-based panels to the carbon pool in year i; $\Delta\, C(i)$ is the carbon stock change of each wood-based panel during year i.

2.3.2. Selection of Parameters and Data Sources

The basic density of the wood-based panels in this work was adopted from the national standard GB/T 1933–2009, the Method for Determination of the Density of Wood. The moisture content was adopted from the national standard GB/T 1931–2009, the Method for Determination of the Moisture Content of Wood. The carbon fraction was adopted from the published literature data in China [50]. The half-life values and first-order decay rate were based on the default data provided by the 2013 IPCC Guidelines. Table 3 shows the conversion parameters used in the calculation of carbon stocks in wood-based panels. The carbon stock changes were converted to CO_2 by 3.67 [10].

Table 3. Various carbon conversion factors of wood-based panels.

Wood-Based Panels	Density (t/m^3)	Carbon Fraction (%)	Carbon Factor (tc/m^3)	Moisture Content (%)	Half-Life (years)	Decay Rate (K)
Plywood	0.520	0.443	0.230	6	25	0.028
Fiberboard	0.760	0.465	0.353	4	25	0.028
Particleboard	0.620	0.470	0.291	5	25	0.028

Note: various carbon conversion factors of wood-based panels in China are adopted from published studies [11,50].

The data of the total production, import, and export of industrial roundwood and total production of wood-based panels between 1990 and 2015 were from the China Forestry Statistical Yearbook. The stock of wood-based panel carbon pool was cumulative. Calculating the carbon stock required values from the previous year. The 2006 IPCC Guidelines recommends that calculation of the carbon stock of HWP starts from 1900 and assumes that the value prior to 1900 is zero [35]. The current production of industrial roundwood and wood-based panels, as well as the trade data recorded in the China Forestry

Statistical Yearbook can be traced back to 1949. Data prior to 1949 can be reverse-calculated using 1949 data as a benchmark in Equation (6) [51].

$$V_i = V_i' \times e^{(u \times (i - i'))} \tag{6}$$

where u is the continuous rate of change in industrial roundwood consumption for China at default data of 0.0217; V_i is the annual production, import, or export of industrial roundwood and various wood-based panels in year i tracing back to 1900; V_i' is the annual production, import, or export of industrial roundwood and various wood-based panels in the benchmark year; i is the year; i' is the benchmark year.

3. Results

3.1. CO_2 Emissions

The annual CO_2 emissions in the production of the wood-based panel industry were derived and are shown in Figure 3.

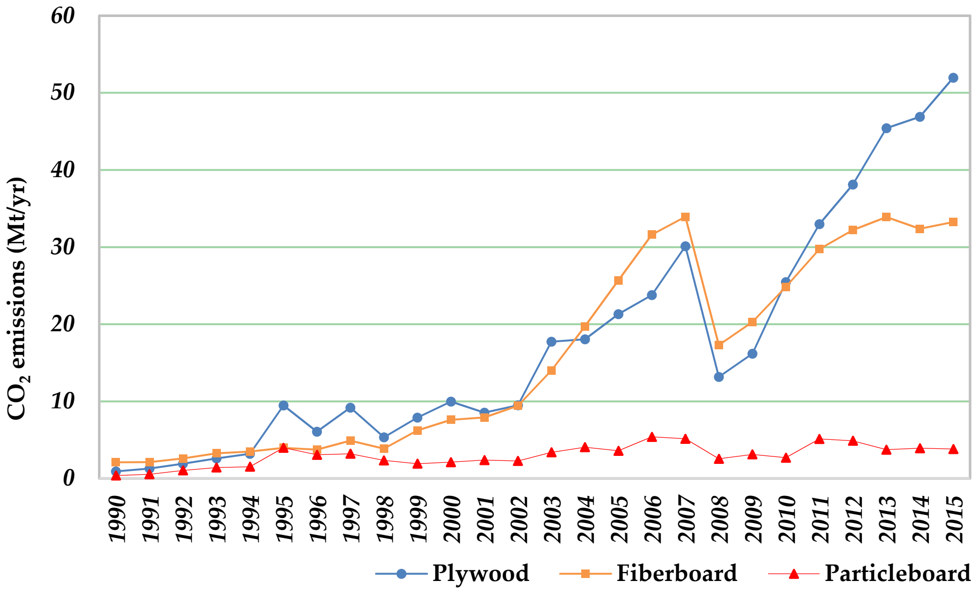

Figure 3. On-site CO_2 emissions for the manufacture of China's wood-based panels.

The numbers of standard coal were converted to CO_2 with a conversion coefficient of 2.54 t CO_2/tce [52]. On-site CO_2 emissions for manufacturing plywood, fiberboard, and particleboard were 1.30, 1.91, and 0.95 t CO_2/m^3, respectively, during the period 1990–2007. From the production and trade data in the China Forestry Statistical Yearbook, the average annual CO_2 emitted to the atmosphere was found to be 7.80 Mt in the first stage.

In the second stage, China's wood-based panel industry experienced a new round of rapid growth, with an average annual yield of 171.96 million m^3. On-site manufacturing of 1 m^3 of plywood, fiberboard, and particleboard produced 0.51, 0.81, and 0.30 t CO_2, respectively. The average annual CO_2 emitted to the atmosphere was 21.84 Mt CO_2, which is 1.8 times of the first stage, due to the rapid growth of yields and low energy consumptions.

Total CO_2 emission was found to grow in each stage. The annual CO_2 emissions of plywood manufacturing were the highest at approximately 17.58 Mt/year and were followed by those of fiberboard (15.78 Mt/year). Particleboard had the lowest annual CO_2 emission contributions due to the low yields and CO_2 emission per unit.

3.2. CO_2 Stock Changes

Forests sequester atmospheric CO_2 to produce wood, and carbon stored in wood products is emitted as CO_2 and CH_4 when burned [53]. As shown in Figure 4, China's annual CO_2 stock changes of wood-based panels continuously increased from 1990 to 2015. Using established national data and the PA to carbon storage, the net increase in CO_2 stored in 1990 was calculated to be 1.88 Mt whereas it was calculated to be 125.49 Mt in 2015. The annual average increments of plywood, fiberboard, and particleboard were 19.06, 15.70, and 4.98 Mt CO_2, respectively. Plywood had the highest annual output and thus had the most significant changes in CO_2 pool.

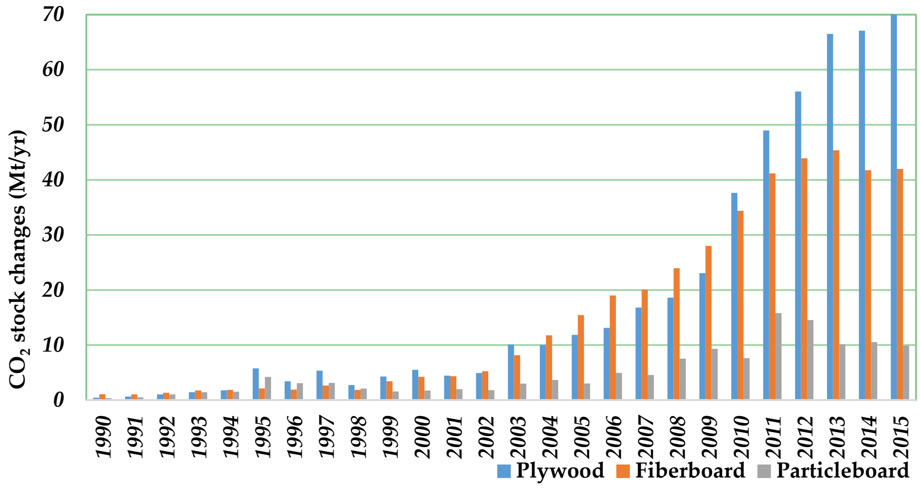

Figure 4. CO_2 stock changes of China's wood-based panels.

The carbon stock of China's HWP products rapidly increased after 2003 mainly due to the rapid development of China's forestry that gained an important position in the sustainable development of China's national economy. After 2001, the production of China's wood-based panels increased at a rapid speed, thereby increasing the annual stock.

3.3. Annual CO_2 Fluxes and Contributions

Figure 5 exhibits the gate-to-product gate CO_2 fluxes of wood-based panels between 1990 and 2015.

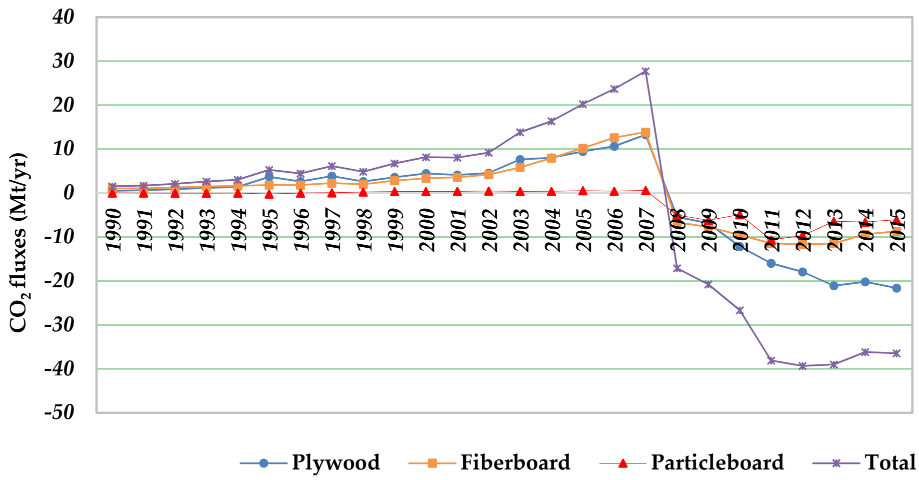

Figure 5. CO_2 fluxes of China's wood-based panels.

Wood-based panel contributions varied from approximately 1.54 Mt CO_2 to 27.74 Mt CO_2/year between 1990 and 2007. The largest emitter was plywood (i.e., 4.61 Mt CO_2/year), followed by fiberboard (i.e., 4.37 Mt CO_2/year) and particleboard (i.e., 0.22 Mt CO_2 CO_2/year). In this stage, wood-based panels were carbon sources and CO_2 emissions of on-site manufacture exceeded the CO_2 stored in the products. The annual CO_2 emission contributions to the atmosphere were 9.20 Mt. With the increase in outputs, China's wood-based panels produced large amounts of CO_2 to the atmosphere.

The implementation of new standards led to the decrease in energy consumption per panel in the second stage. On the contrary, an increasing trend of the production of wood-based panels with an annual growth rate of approximately 25% was observed. In 2008–2015, wood-based panels acted as a carbon sink. CO_2 storage in wood products offset the manufactured CO_2 released to the atmosphere [20]. The average annual CO_2 removal contributions were 31.71 Mt/year, with the contributions of plywood, fiberboard, and particleboard at 15.17, 9.59, and 6.95 Mt CO_2/year, respectively. Considering the same trend with the first stage, plywood played the most important role in removing CO_2. The greater the output, the greater the contributions to CO_2 removal.

The CO_2 contributions between the two stages were the exact opposite. The difference between CO_2 storage and emissions varied from positive to negative; therefore, the wood-based panel pool in China changed from a carbon source to a carbon sink. This finding was mainly due to the fact that energy consumption per panel for on-site manufacture decreased and panel production significantly increased.

4. Discussion

4.1. Methodological and Data Constraints

The underlying assumptions presented in this work can be improved through in-depth analyses such as (1) considering the substitution of emission reduction to decrease the life cycle of GHG emissions, (2) studying the climate change mitigation potential of wood-based panels through the cradle-to-grave system boundary, and (3) achieving acute and specific data and methods. Some methodological and data constraints are discussed below.

Analysis based on default data and methods presents a methodological weakness, because of the absence of available data. The accuracy and quality of results in this work depended on the data and method quality. Using the default data and methods provided by IPCC and previous publications introduced uncertainties. This work calculated the CO_2 stock changes based on the default half-lives that were distinguished among main wood-based panels. A total of 25 years were used as half-lives in the current work whereas some studies estimated them to be shorter than 25 years [50,51]. This work might have overestimated the CO_2 stock changes.

The 2013 IPCC Guidelines describes three methods based on the level of detail and accuracy of the available data: (1) instantaneous oxidation (Tier 1), (2) first-order decay (Tier 2), and (3) country-specific methods (Tier 3). The country-specific method can be used if a large number of detailed data and methodologies are available. Under the Tier 3 method, accurate country-specific information is applied to improve the accuracy of the estimates. If consistent, transparent, and verifiable parameters (i.e., service life information and conversation factors of products) are applied to country-specific methods, then the estimates of carbon removal contributions can increase in accuracy and reliability.

The current national environmental standard for the wood-based panel industry stipulates that imported wooden raw materials should come from sustainable forests and that national wooden raw materials should comply with the forestry laws and regulations in China [54]. The carbon in wood-based panels is allocated to particular forest activities because different estimates of contributions depend on the wood origin. The harvest from deforestation is regarded as instantaneous oxidation. This work disregarded deforestation activities because of the lack of data. Thus, the CO_2 contributions were overestimated. Forest activities should be differentiated in the future.

4.2. Potential of China's Wood-Based Panels in Reducing CO_2 Emissions of On-Site Manufacture

The wood-processing industry standard in China has a low requirement in energy consumption indexes [55]. The energy consumption per unit output of China's wood-based panel is 4.8 times that of the world [56]. As presented in Table 4, CO_2 emissions during the wood-based panel production were higher in China than those in the United States. The gate-to-gate life cycle CO_2 fluxes of China's wood-based panels were lower than those of the United States. China's wood-based panel industry has a high CO_2 emission reduction potential in on-site manufacture.

Table 4. CO_2 fluxes through the gate-to-gate life cycle of wood-based panels in China and the United States (t/m^3).

Countries		Wood-Based Panels		CO_2 Emissions	CO_2 Stocks	CO_2 Fluxes
China	First stage	Plywood		1.30	0.85	0.45
		Fiberboard		1.91	1.30	0.61
		Particleboard		0.95	1.07	−0.12
	Second stage	Plywood		0.51	0.85	−0.34
		Fiberboard		0.81	1.30	−0.49
		Particleboard		0.30	1.07	−0.77
USA		Plywood	PNW	0.13	0.84	−0.71
			SE	0.20	0.98	−0.78
		Fiberboard		0.08	1.27	−1.19
		Particleboard		0.18	1.05	−0.87

Note: CO_2 emissions and stocks of wood-based panels in the United States are adopted from Consortium for Research on Renewable Industrial Materials Report [57]. The carbon calculation of plywood is divided into two types on the basis of region: PNW (Pacific Northwest) and SE (Southeast).

However, the decrease in energy consumption indexes for wood-based panel production indicates that China's wood-based panels can potentially reduce CO_2 emissions of on-site manufacture. China is committed to reducing or avoiding pollutant emissions during production, service, and use. The implementation of cleaner production technologies reduces or eliminates pollution from the environment by improving the technologies and using clean materials. For more than 10 years, the index values of total energy consumption standards have declined. The reduction in energy consumption during production shows that China's wood-based panels present strong GHG reduction capacity and energy-saving potential.

4.3. Ways to Enhance CO_2 Removal Contributions of China's Wood-Based Panels

Climate change can be mitigated through the use of wood products that reduce carbon emissions and remove carbon [58,59]. Global carbon emissions can be mitigated using two methods: (1) directly reducing carbon emissions and (2) indirectly increasing carbon storage [60].

Cleaner production technologies must be carried out to reduce energy and resource consumption in production and thus reduce CO_2 emissions [14]. Energy consumption occupies a large proportion in the cost of wood-based panel products; the energy costs of plywood, fiberboard, and particleboard are 25%, 30%, and 30%, respectively [46,61,62].

Carbon mitigation or slowing carbon emissions over time can also be achieved using various CO_2 stock approaches, such as extending the life span of HWP, recycling and reusing disposed HWPs, and improving the production efficiency of HWPs. These approaches cannot directly mitigate carbon emissions or indirectly increase carbon storage. However, they can provide a significant time lag between carbon sequestration from the atmosphere and carbon emissions back into the atmosphere [60].

4.4. Nature of Cleaner Production Technologies in China's Wood-Based Panel Industry

Cleaner production is based on holistic and preventative approaches; if this technology is implemented society-wide, then societies can be sustainable [63]. Cleaner production has been adopted by China as a primary tool to fight against industrial pollution [64]. During the 12th Five-Year Plan (2011–2015), the energy consumption per unit of GDP fell by approximately 16% compared with the 1.03 tce in 2010 [65]. To achieve national emission reduction targets, cleaner production technologies have been applied in China's wood-based panel industry. The values in Table 5 show the grades for cleaner production technologies in wood-based panel production.

The first grade represents the advanced level of international cleaner production, the second grade represents the advanced level of cleaner production in China, and the third grade represents the basic level of cleaner production in China.

China's energy consumption standards for wood-based panels have been revised in recent years (Tables 1 and 2) and energy consumptions for production of 1 m^3 of wood-based panels have decreased. These amendments conform to the requirements of cleaner production t in China.

Table 5. Indexes of cleaner production technologies for wood-based panel production in China (kgce/m^3).

Wood-Based Panels	Indexes	Values
Fiberboard	First grade	$q_1 \leq 200$
	Second grade	$q_1 \leq 390$
	Third grade	$q_1 \leq 440$
Particleboard	First grade	$q_1 \leq 120$
	Second grade	$q_1 \leq 150$
	Third grade	$q_1 \leq 200$

Note: the arrangement is based on two standards: Cleaner Production Standard-Wood-Based panel Industry (Medium-density Fiberboard) and Cleaner Production Standard-Wood-Based panel Industry (Particleboard).

Another reason for the decrease in energy consumption for production of 1 m^3 of wood-based panels was the large increase in output. The comprehensive energy consumption per unit output of an enterprise in actual production refers to the ratio of total energy consumption to qualified output in the same statistical period. Clean production technologies reduce the total energy consumptions for on-site manufacture. An increase in output means low energy consumption per unit of product.

5. Conclusions

China is one of the major countries that aim to reduce GHG emissions. As a pillar of the forestry industry, the production and use of wood-based panels in China have a significant impact on the contribution of GHGs. Assessing the life cycle of CO_2 fluxes revealed the role of China's wood-based panel industry in mitigating climate change and quantifying CO_2 emission and removal contributions in different panels. For our analysis, we estimated CO_2 emissions through product production and CO_2 stored during their useful lives. The results showed that China's wood-based panels were carbon sources between 1990 and 2007. As implied by the energy consumption standards for wood-based panel production, energy consumption per panel for on-site manufacture decreased. Panel production in China also increased considerably. The two factors had made China's wood-based panels a carbon sink in 2008–2015. Between the two stages, plywood produced the largest contributions whereas particleboard provided the smallest contributions. The changes in annual CO_2 fluxes showed that the use of wood-based panels met the GHG emission targets in China. Therefore, cleaner production technologies must be carried out to reduce energy consumption and GHG emissions in panel production. China's wood-based panels, with good prospects and strong demands projected in the future, can potentially contribute to climate change mitigation.

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Abbreviations

The following abbreviations are used in this manuscript:

AFA	Atmospheric flow approach
C	Carbon
COP	Conference of the parties
GDP	Gross domestic product
GHG	Greenhouse gas
HWP	Harvested wood products
IPCC	Intergovernmental panel on climate change
LY/T 1529–1999	Total energy consumption in plywood production
LY/T 1451–1999	Comprehensive energy consumption for hard fiberboard production on the wet process
LY/T 1530–1999	Total energy consumption in particleboard production
LY/T 1529–2012	Comprehensive energy consumption of plywood production
LY/T 1451–2008	Overall energy consumption for fiberboard production
LY/T 1530–2011	Comprehensive energy consumption of particleboard production
MDF	Medium-density fiberboard
Mt	Million ton
PA	Production approach
SCA	Stock change approach

References

1. Shrestha, R.M.; Rajbhandari, S. Energy and environmental implications of carbon emission reduction targets: Case of Kathmandu Valley, Nepal. *Energy Policy* **2010**, *38*, 4818–4827. [CrossRef]
2. Li, S.; Fang, H.; Liu, C. *Report on Low-Carbon Economy Development in China*; Science Press: Beijing, China, 2011.
3. Schelhaas, M.J.; Cienciala, E.; Lindner, M.; Nabuurs, G.J.; Zianchi, G. *Selection and Quantification of Forestry Measures Targeted at the Kyoto Protocol and the Convention on Biodiversity*; Alterra (Alterra-Rapport 1508): Wageningen, The Netherlands, 2007.
4. Jochem, D.; Janzen, N.; Weimar, H. Estimation of own and cross price elasticities of demand for wood-based products and associated substitutes in the German construction sector. *J. Clean. Prod.* **2016**, *137*, 1216–1227. [CrossRef]
5. The State Forestry Administration of the People's Republic of China. *China Forestry Statistical Yearbook*; Chinese Forestry Press: Beijing, China, 2016; Available online: http://www.lknet.ac.cn/ (accessed on 12 December 2016).
6. Zhang, X.; Yang, H. The dynamic evolution of China's wood-based panel industry based on global equilibrium. *For. Econ.* **2015**, *1*, 62–74.
7. Karjalainen, T.; Pussinen, A.; Liski, J.; Mohren, G.M.J. An approach towards an estimate of the impact of forest management and climate change on the European forest sector carbon budget: Germany as a case study. *For. Ecol. Manag.* **2002**, *162*, 87–103. [CrossRef]
8. Yang, H.; Zhang, X.; Hong, Y. Classification, production, and carbon stock of harvested wood products in China from 1961 to 2012. *Bioresources* **2014**, *9*, 90–95. [CrossRef]

9. Bergman, R.; Puettmann, M.; Taylor, A.; Skog, K.E. The carbon impacts of wood products. *For. Prod. J.* **2014**, *64*, 220–231. [CrossRef]
10. Wilson, J.B. Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. *Wood Fiber Sci.* **2010**, *42*, 107–124.
11. Intergovernmental Panel on Climate Change. *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2014; Available online: http://www.ipcc-nggip.iges.or.jp/public/kpsg/index.html (accessed on 10 March 2016).
12. Heath, L.S.; Maltby, V.; Miner, R.; Skog, K.E.; Smith, J.E.; Unwin, J.; Upton, B. Carbon and carbon profile of the U.S. forest products industry value chain. *Environ. Sci. Technol.* **2010**, *44*, 3999. [CrossRef] [PubMed]
13. Ji, C.; Cao, W.; Chen, Y.; Yang, H. Carbon balance and contribution of HWP in China based on the production approach of the intergovernmental panel on climate change. *Int. J. Environ. Res. Public Health* **2016**, *13*, 113. [CrossRef] [PubMed]
14. Pan, Y.; Shen, J.; Wang, Y. Study on environmental impact assessment of wood-based panel based on LCA method. In Proceedings of the 5th International Conference on Bioinformatics and Biomedical Engineering, Wuhan, China, May 2011; pp. 1–4.
15. Syahirah, J. Environmental impact Assessment of Raw Material Input and Production Process on Malaysian Wood-Based Panel Products. Master's Thesis, Universiti Teknologi MARA, Kuala Lumpur, Malaysia, 2015.
16. Laurent, A.; Olsen, S.I.; Hauschile, M.S. Carbon footprint as environmental performance indicator for the manufacturing industry. *Cirp. Ann.-Manuf. Technol.* **2010**, *59*, 37–40. [CrossRef]
17. Wilson, J.B. Life-cycle inventory of particleboard in terms of resources, emissions, energy and carbon. *Wood Fiber Sci.* **2010**, *42*, 90–106.
18. Wilson, J.B.; Sakimoto, E.T. Gate-to-gate life-cycle inventory of softwood plywood production. *Wood Fiber Sci.* **2005**, *37*, 58–73.
19. Garcia, R.; Freire, F. Environmental assessment of wood-based panels: A comparison of life-cycle-based tools. *Int. J. Sustain. Constr.* **2012**, *1*, 2182–2743.
20. Bergman, R.D.; Kaestner, D.; Taylor, A.M. Life cycle impacts of north American wood panel manufacture. *Wood Fiber Sci.* **2016**, *48*, 40–53.
21. Robson, D.; Sadler, P.; Newman, G. Carbon sequestered in UK forest products and wood based panels in construction: Helping to meet UK's greenhouse gas emission reduction targets. *Int. Wood Prod. J.* **2014**, *5*, 139–145. [CrossRef]
22. Lee, J.Y.; Lin, C.M.; Han, Y.H. Carbon sequestration in Taiwan harvested wood products. *Int. J. Sust. Dev. World* **2011**, *18*, 154–163. [CrossRef]
23. Xiang, S.; Wei, X.; Liu, W. Evaluation of the environmental properties of particle boards from a life cycle angle. *J. Cent. South Univ. For. Technol.* **2007**, *27*, 166–168.
24. Xue, Y.; Xiang, S.; Liu, W. Life cycle assessment of MDF. *For. Sci. Technol.* **2006**, *31*, 47–49.
25. West, T.O.; Marland, G.A. Synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric. Ecosyst. Environ.* **2002**, *91*, 217–232. [CrossRef]
26. Tillman, A.M.; Ekvall, T.; Baumann, H. Choice of system boundaries in life cycle assessment. *J. Clean. Prod.* **1994**, *2*, 21–29. [CrossRef]
27. Rivela, B.; Hospido, A.; Moreira, M.T.; Feijoo, G. Life cycle inventory of particleboard: A case study in the wood sector. *Int. J. Life Cycle Assess.* **2006**, *11*, 106–113. [CrossRef]
28. Sandin, G.; Peters, G.M.; Svanström, M. *Life Cycle Assessment of Forest Products: Challenges and Solutions*; Springer International Publishing: Cham, Switzerland, 2016; Volume 1, pp. 25–67.
29. Pingoud, K.; Soimakallio, S.; Pussinen, A. Greenhouse gas impacts of harvested wood products: Evaluation and development of methods. *VTT Tiedotteita–Valtion Teknillinen Tutkimuskeskus* **2003**, *2189*, 3–120.
30. Kouchakipenchah, H.; Sharifi, M.; Mousazadeh, H.; Zareahosseinabadi, H.; Nabavupelesaeaei, A. Gate to gate life cycle assessment of flat pressed particleboard production in Islamic Republic of Iran. *J. Clean. Prod.* **2016**, *112*, 343–350. [CrossRef]
31. Chu, J.; Duan, X.; Zhang, R. Development path of wood-based panel industry under low-carbon economy. *World For. Res.* **2013**, *26*, 84–88.
32. The State Forestry Administration of the People's Republic of China.

33. The State Forestry Administration of the People's Republic of China. *Comprehensive Energy Consumption for Hard Fiberboard Production on Wet Process*; Standards Press of China: Beijing, China, 1989; pp. 623–626.
34. The State Forestry Administration of the People's Republic of China. *Total Energy Consumption in the Particleboard Production*; Standards Press of China: Beijing, China, 1989; pp. 1–6.
35. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available online: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm (accessed on 10 March 2016).
36. Marcus, K. A multi-tiered approach for assessing the forestry and wood products industries' impact on the carbon balance. *Carbon Balance Manag.* **2015**, *10*, 4.
37. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
38. Hussain, M.; Malik, R.N.; Taylor, A. Carbon footprint as an environmental sustainability indicator for the particleboard produced in Pakistan. *Environ. Res.* **2017**, *155*, 385–393. [CrossRef] [PubMed]
39. Kouchakipenchah, H.; Sharifi, M.; Mousazadeh, H.; Zareahosseinabadi, H. Life cycle assessment of medium-density fiberboard manufacturing process in Islamic Republic of Iran. *J. Clean. Prod.* **2016**, *112*, 351–358. [CrossRef]
40. The State Forestry Administration of the People's Republic of China. *Comprehensive Energy Consumption of Plywood Production*; Standards Press of China: Beijing, China, 2012; pp. 1–10.
41. The State Forestry Administration of the People's Republic of China. *Overall Energy Consumption for Fiberboard Production*; Standards Press of China: Beijing, China, 2008; pp. 1–4.
42. The State Forestry Administration of the People's Republic of China. *Comprehensive Energy Consumption of Particleboard Production*; Standards Press of China: Beijing, China, 2011; pp. 1–6.
43. Cong, X.; Zhao, S. Study on application of cleaner production of forestry enterprises. *Appl. Energy Technol.* **2014**, *3*, 16–18.
44. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. *Technical Requirements of Cleaner Production for Wood-Based Panel Industry*; Standards Press of China: Beijing, China, 2013; pp. 1–12.
45. Li, H. *Energy Consumption Analyze and Energy-Conserving Technology of Medium and Small-Scale MDF Enterprise*; Central South Forestry University: Changsha, China, 2005.
46. Li, X. *Research of Typical Particleboard Enterprise's Comprehensive Energy Consumption of Unit Product and Energy Saving Programs*; Nanjing Forestry University: Nanjing, China, 2011.
47. Vengala, J.; Nath, S.K.; Pandey, C.N. Energy consumption of wood-based panel products: A review. *J. Indian Acad. Wood Sci.* **2011**, *8*, 80–83. [CrossRef]
48. United Nations Framework Convention on Climate Change. Decisions Adopted by the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol. 2012. Available online: http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf (accessed on 28 May 2016).
49. Yang, H.; Zhang, X. A rethinking of the production approach in IPCC: Its objectiveness in China. *Sustainability* **2016**, *8*, 216. [CrossRef]
50. Bai, Y.; Jiang, C.; Lu, D.; Zhu, Z. Carbon stock change of HWP in China. *J. Zhejiang For. Coll.* **2007**, *24*, 587–592.
51. Guo, M.; Guan, X.; Li, J. Carbon storage and carbon emission of wood forest products in China. *China Popul. Resour. Environ.* **2010**, *20*, 19–21.
52. Tu, H.; Liu, C. Calculations of CO_2 emissions of standard coal. *Coal Qual. Technol.* **2014**, *2*, 57–60.
53. Brunet-Navarro, P.; Jochheim, H.; Muys, B. Modelling carbon stocks and fluxes in the wood product sector: A comparative review. *Glob. Chang. Biol.* **2016**, *22*, 2555. [CrossRef] [PubMed]
54. Ministry of Environmental Protection of the People's Republic of China. *Technical Requirement for Environmental Labeling Products-Wood-Based Panels and Finishing Products*; China Environmental Science Press: Beijing, China, 2010; pp. 1–6. Available online: http://www.sepacec.com/cs/rzbz/201006/W020100612553147617000.pdf (accessed on 10 October 2016).
55. Zhang, Q.; Zhou, D. The approach to enhancing comprehensive strength of China's wood-based panel industry. *China For. Prod. Ind.* **2005**, *32*, 3–5.
56. Guo, S. Energy saving in MDF plant. *China For. Prod. Ind.* **2002**, *29*, 39–41.

57. Puettmann, M.E.; Bergman, R.; Hubbard, S.; Johnson, L.; Lippke, B.; Oneil, E.; Wagner, F.G. Cradle-to-gate life-cycle inventory of US wood products production: CORRIM Phase I and Phase II products. *Wood Fiber Sci.* **2010**, *42*, 15–28.
58. Pingoud, K.; Perälä, A.L.; Pussinen, A. Carbon dynamics in wood products. *Mitig. Adapt. Strat. Glob. Chang.* **2001**, *6*, 91–111. [CrossRef]
59. Profft, I. Contribution of harvested wood products to carbon sequestration-recent trends in Thuringia. *For. Und Holz* **2010**.
60. Lun, F.; Liu, M.; Zhang, D.; Li, W.; Liu, J. Life cycle analysis of carbon flow and carbon footprint of harvested wood products of larix principis-rupprechtii in China. *Sustainability* **2016**, *8*, 247. [CrossRef]
61. Deng, J.; Zhang, J.; Li, H. Discussion on energy-saving measures of plywood enterprises in China. *China For. Prod. Ind.* **2010**, *37*, 33–35.
62. Huang, Z. Energy consumption analysis and energy saving technology of medium density fiberboard. *Silicon Valley* **2014**, *19*, 151–152.
63. Yong, J.Y.; Klemeš, J.J.; Varbanov, P.S.; Huisingh, D. Cleaner energy for cleaner production: Modelling, simulation, optimisation and waste management. *J. Clean. Prod.* **2016**, *111*, 1–16. [CrossRef]
64. Zhang, B.; Yang, S.; Bi, J. Enterprises' willingness to adopt/develop cleaner production technologies: An empirical study in Changshu, China. *J. Clean. Prod.* **2013**, *40*, 62–70. [CrossRef]
65. Shen, J.; Xue, S.; Zeng, M.; Wang, Y.; Wang, Y.; Liu, X.; Wang, Z. Low-carbon development strategies for the top five power generation groups during China's 12th Five-Year Plan Period. *Renew. Sustain. Energy Rev.* **2014**, *34*, 350–360.