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Life Cycle Assessment of Complex Forestry Enterprise: A Case Study of a Forest–Fiberboard Integrated Enterprise

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Abstract: The complex forestry enterprises incorporate the production activities of different links in the value chain of forest products and should be the mainstay for the sustainable forestry production of China in the foreseeable future. This case study was carried out and main data were collected in a forest–board integrated enterprise of South China. A life cycle model using the impact 2002+ method was applied to identify the resource consumption and environmental impacts of different production stages along the industrial chain. This study incorporates the calculation of carbon sequestration per unit output into the standard LCA to evaluate the effect of the forest cultivation stage. The objective of this study is two-fold. The first objective is to gain a better understanding of the environmental impacts of the complex forestry enterprises. The second objective is to put forward environmental management suggestions for the identified hotspots along the forest value chain. Factors affecting the environment include carbon sequestration and seedlings, electric power, and the use of wood fuel. Improvement suggestions are put forward from three perspectives: Changing the type and application method of fertilizer, reducing electric power consumption, and reducing wood fuel consumption.

Keywords: environmental management; hotspot analysis; complex forestry enterprise; forest–fiberboard integrated; life cycle assessment

1. Introduction

To meet new economy-developing standards, there has emerged an urgent need for higher levels of coordination and integration in the field of ecological economy. The traditional management mode is no longer a preferred choice for a sustainable future due to the problems of over-exploitation of natural resources and environmental pollution [1]. However, with the promotion of China's position in the international value chain, some 'forest–paper integration', 'forest–board integration', and 'forest industry' enterprises or conglomerates have emerged in China. These types of forestry enterprises will become the main force of China's forestry development [2].

According to the annual reports and other published information, such enterprises are usually highly organized, specialized, and are allocated with large-scale production benefits. At the same time, the production and operation of these enterprises also include a variety of forest products. However, our field survey shows that the integration strategy of these enterprises is just a formality. The integration of these groups is usually achieved through mergers and investments. In practice, the parent company or subsidiary companies of each business department often continue with their original business modes, and then operate independently. There is a lack of integrated ecological management approaches among the enterprise groups. Nevertheless, this integration strategy often does not work, since it cannot really help enterprises to enhance competitiveness or achieve sustainable development.

The objects of production of forestry enterprises are mainly forest products, comprising a product system with multiple types and values. In a broad sense, forest products include wood-based forest products, non-wood forest products that provide economic and social values, forest recreation services that are mainly used for human consumption, and other appearance system services that possess the function of protecting biodiversity or carbon storage [3]. This study redefines the concept of forest products from the perspective of micro-enterprises.

For the better understanding of this study, Table 1 displays the full names of the acronyms used in this paper.

Table 1. Summary of the acronyms.

Acronyms	Full Name
FAO	Food and Agriculture Organization of the United Nations
LCA	Life cycle assessment
ISO	International Organization for Standardization
SIA	Sustainability impact assessment
ALCA	Attributive life cycle assessment
CLCA	Contingency life cycle assessment
ILCD	International reference life cycle data system
FU	Function unit
MDF	Medium-density fiberboard
COD_{Cr}	Chemical oxygen demand measured by potassium dichromate ($K_2Cr_2O_7$) as oxidant
BOD_5	Biochemical oxygen demand in 5 days
SS	Suspended solid
C-G	Cradle to gate

Referring to the definition of forest products in a narrow sense in the documents of the Food and Agriculture Organization of the United Nations (FAO) [4], this study expands the concept of forest products. Considering the social requirements for the production- and service-oriented functions of forestry enterprises, we redefine forest products in a broad sense as: (1) Wood in rough, i.e., logs with main stems and branches removed; (2) raw materials from primary processing of round wood, i.e., lengthwise wood swan, veneer sheets, railroad sleepers, residues of wood pressing (like wood chips and particles, or pulp of wood); (3) industrial materials from deep processing, which are manufactured from a number of sources (groups 1 and 2), i.e., wood-based panels (generally classified into plywood, particle board, and fiberboard), paper, and paperboard; (4) waste paper and recyclable wood products; (5) forest management services, i.e., reforestation and forest recreation. This concept maintains the wood-based material attributes of forest products emphasized in the FAO's definition and complements the basic attributes of ecological services of forest products.

The concept of the value chain of forest products [5] has been further improved and enriched from the birth of this terminology. The value chain of forest products refers to a complex network or system formed by the enterprises that produce or provide forest products of different levels and categories in the vertical and horizontal links of the industrial chain in order to obtain more added value. The concept of the complex forestry enterprise is brought up based on the concept of the value chain of forest products.

In this study, a complex forestry enterprise is referred to as a cross-industry enterprise (conglomerate) that relies on the value chain of forest products. Its business activities include the products or services that consist of economic forest management (sale, use, and waste treatment), wood product processing (including primary and secondary), and biological refinement and production. These business activities create economic, ecological, and social values by delivering products or services, such as seedlings, wood-based materials, energy, and environmental services, to social production [6].

The commercial activities of complex forestry enterprises have multiple impacts on the environment. Resource consumption and production wastes during the process will be detrimental to both the environment and human health [7]. Relatively speaking, forest cultivation can produce a positive impact on climate change by absorbing carbon dioxide [8]. Consequently, for such enterprises, attention should be paid to the environmental load of different production stages in the industrial chain. Life cycle assessment (LCA) is the method that can comprehensively analyze the environmental impacts of various links in the life cycle [9], which can provide a decision-making basis for the effective environmental management of enterprises and the realization of the sustainable development goals of saving resources and reducing emissions [10].

A study on LCA for forestry enterprises is a relatively new attempt. There are different production and management activities in the value chain of forest products. Studies on LCA for forestry can be divided into three categories: (1) Evaluation of forest management activities, involving forest cultivation [11], logging, and transportation [12,13]; (2) evaluation of processing activities, including the production of traditional wood-based products, such as wood processing [14], decorative boards [15–17], and floors [18]; (3) evaluation of conversion activities of wood-based products, mainly referring to biological refinement [19,20]. The first two research approaches are usually relatively independent. Only the upstream of the value chain of forest products or a single link of field production are analyzed. At the same time, the latter focuses on regional environmental impacts. However, some studies have been developed for bio-refinement, which also involves multiple industries [21]. In addition, Janine Schweier (2019) proposed a theoretical framework for applying LCA to sustainability impact assessment (SIA) to evaluate the environmental, economic, and social performance of forest operations [22]. To the best of our knowledge, there are no published LCAs for forestry enterprises that cross the industry chain. In this sense, this study aims to identify the resource consumption and environmental impacts of different production stages along the industrial chain of complex forestry enterprises, and to put forward environmental management suggestions for the designated environmental impact hotspots on the forest value chain.

In this research, a case study method was employed to capture as many details as possible and to create in-depth insights [23]. A limited-scope life cycle assessment (LCA) procedure for a forest–board integration enterprise has been developed using thorough process theories and inventory data. The intended audience of the results of this study includes other LCA professionals, forest industry companies, environmental managers, government regulators, and bio-fuel developers. The results and methods of this study may be later used at different levels of data aggregation when considering industrial ecology and symbiosis or seeking sustainable survival and competitiveness.

2. Materials and Methods

2.1. Case Study System Boundaries

The investigated case study is one of the typically integrated enterprises of forest production in the collective forest area of South China. The examined case study consists of a forest cultivation subsidiary A and a fiberboard production subsidiary B. The business activity of subsidiary A is comprised of three stages: Harvesting, tending, and protection. Most of the forests in South China are in mountainous areas, in which it is difficult for heavy forestry machinery and equipment to operate, so the planting and felling activities are completed by humans or with chainsaws. The transportation means in these forest areas are merely small four-wheel-drive agricultural vehicles. The specification of the fiberboard produced by subsidiary B is 4 × 8 feet, with a thickness of 9–30 mm—mostly 15 and 18 mm. The production process goes through material preparation (including chipping and refining), fiber preparation (including mixing and drying), forming, and sawing.

2.2. Goal and Scope

According to International Organization for Standardization (ISO) 14040 and ISO 14044, the starting point of LCA evaluation research is to define the research objectives. At this stage, the application field of LCA results, research motivation, target audience, and the question of whether it is a published comparative study should be considered. Clear objectives are also necessary factors to elaborate on the results attentively [24]. The goal of the definition aims to clarify the scientific issues that are closely related to the choice of the LCA methodology. The impact of the decision of attributive LCA (ALCA) or contingency LCA (CLCA) will run through the whole LCA process, for example, whether the inventory data input uses average data or marginal data [25]. Therefore, it should be made clear together with the research issues [26].

In terms of inventory data collection, ALCA accounts for the real-time physical flow on the time interface selected in a life cycle, while CLCA is adopted to detect the flow changes caused by decision-making, which can reflect the environmental results generated by these changes [27,28]. In the international reference life cycle data system (ILCD) handbook, the static technology of ALCA can be used to describe the actual or predicted supply chain and the value chain from use to the end of life based on a specific or generic unit process. CLCA is a dynamic technology for adding the expected response to the change of different product demands. The ILCD handbook provides three further LCA scenarios: (1) Micro-decision-making (product), such as product-specific improvement, comparison, and process; (2) macro-decision-making (policy), national or global policy improvement and impact assessment, for example; (3) accounting (product and policy); for instance, descriptive environmental reporting on enterprises. Scholars hold different perspectives on ALCA, CLCA, and existing standards or guidelines, so they have not made explicit provisions yet. Consequently, there is still controversy about whether this methodology is applicable to scenarios 1 and 2 [25]. This study aims to analyze the environmental impacts of complex forestry enterprises (scenario 3), in which the use of the ALCA methodology has been recognized by the academic community [25,26].

In this study, a complex forestry enterprise was investigated with the ALCA methodology. Considering that the environmental impacts of enterprises originate from production activities, the goal of this LCA study is to evaluate the environmental load of each production stage and to propose methods of improving ecological impact for recognized hotspots. This study incorporates the carbon sequestration in the standard LCA calculation to assess the impacts of climate change for business activities in the forest cultivation stage of complex forestry enterprises.

2.3. Functional Unit and Allocation

The functional unit (FU) is the quantification of product system performance in the reference unit. Although it is considered that functional units should be unified to achieve comparable results [29], ISO 14040 and ISO 1404 emphasized that functional units should be consistent with research objectives. Therefore, some studies suggest that different functional units should be set up for different types of research [26]. In related researches, functional units are usually divided into two types, named 'output-related' and 'input-related'. Input-related functional units are used to compare the input of different raw materials or different unit processes of a product system, while output-related functional units are usually used in the research of specific products or primary products [30,31]. Output-related functional units can be further decomposed into 'single product', 'function of a single product', and 'multi-functional' functional units [26]. Although certain problems could be avoided in input-related functional units, there are co-products or by-products in most production systems. Therefore, the multi-functional output-related functional unit is usually closer to the actual situation [31].

The complex forestry enterprises provide multiple types of products with a core and multi-layer structure [6]. Nevertheless, it is impossible to represent the whole enterprise with a particular main product. In this study, multi-functional output-related functional units are used to evaluate the basic flow and product flow of all products in the whole system. For the fiberboard production stage in subsidiary B (as a core layer), following the research of [32], the functional unit is thus defined as 1.0 m^3 of medium-density fiberboard (MDF) with an average thickness of 16 mm and an average density of 710 kg/m^3 (dry base, without humidity), without a surface coating. Simultaneously, since this study does not contain the assessment for the subsequent use of fiberboard and is not a comparison of LCA, service life reference still has not been specified, following Reference [33]. No geographical boundary has been set, and the technical level is the actual production level of the enterprises and the local average level. The forest owned by subsidiary A (as an extension layer) is mainly used for the production of Chinese fir and Masson pine. Residues, firewood, and other wastes are transferred to the downstream enterprises within the group. They are used as raw materials for the production of fiberboard rather than being left in the forest or incinerated. A total of 1 m^3 wood biomass is used in this study as the functional unit to reflect not only differences in the biomass, but also those of the soil composition and climatic characteristics.

The proportion of by-products in fiberboard production is tiny (3.9%) and does not affect the accuracy of the study. So, there is no distribution problem involved in fiberboard manufacturing enterprises [33]. In contrast, forest cultivation enterprises are multi-functional production systems that produce a variety of products. Normally, the product system is divided into main products, co-products, by-products, and wastes, and the environmental load needs to be distributed among different products [26]. In this research area, residual wood-based biomass is generally divided into by-products or waste, and only by-products are considered in the distribution of environmental load. In contrast, the impact of waste on the environment is considered as 0 [34]. Allocation can be avoided in this study through two ways: One is to expand the system boundary; the other is to change the forest resource subsystem into a single output system. The various outputs of forest cultivation enterprises (such as timber, residues, firewood, etc.) are all wood-based biomass in terms of material composition. To avoid allocation, they are treated as the same product by changing the forest resource subsystem into a single output system.

2.4. System Boundaries

The system boundary begins with operation in the forest (i.e., cradle) and ends with fiberboard production (i.e., product gate) (Figure 1), which consists of two subsystems. The forest resource system boundary may include silvicultural operations, which include site preparation, planting or regeneration, and forest management, harvesting, and hauling (Figure 2). Site preparation changes the physical properties of the soil by cut-over clearing and soil scarifying. The forest of subsidiary A, of this case, is a mountainous area. Therefore, site preparation and the subsequent planting process are carried out manually by workers carrying plants or seedlings and equipped with hoe and spade. The process of forest management usually involves clearing, fertilization, application of pesticides and herbicides, and thinning. However, subsidiary A is involved in forest certification, and therefore, fertilizers or pesticides are not used. The process of harvesting includes logging and skidding. The transaction will be made with its buyers in the auction of the standing timber produced by subsidiary A. The processes of skidding and transportation of the timber are completed by them as well. So, the environmental impacts of these processes are not considered in the assessment of subsidiary A. In this study, hauling only refers to the transportation of cutting residues and firewood (as the raw material for the fiberboard production) to subsidiary B as well. Lastly, activities involving human resources are not included in the boundary. The main steps of on-site fiberboard production include material preparation, conditioning, and refining (fiber preparation), drying and pressing, and sawing. These steps are further divided into three stages as material preparation (I), fiber preparation (II), and MDF (III). On-site power generation comes from the combustion of waste (wood-based) from the boiler, which is the fourth stage (IV) defined in this study. Due to the lack of data, activities related to seed production, transportation of energy carriers, auxiliary materials, and machinery from industrial output to forest management areas, depletion of biodiversity during tree growth, construction and maintenance of infrastructure (such as roads and fire belts), and the creation of capital goods (machinery, buildings, and roads) for on-site fiberboard production are also excluded from the system boundary.

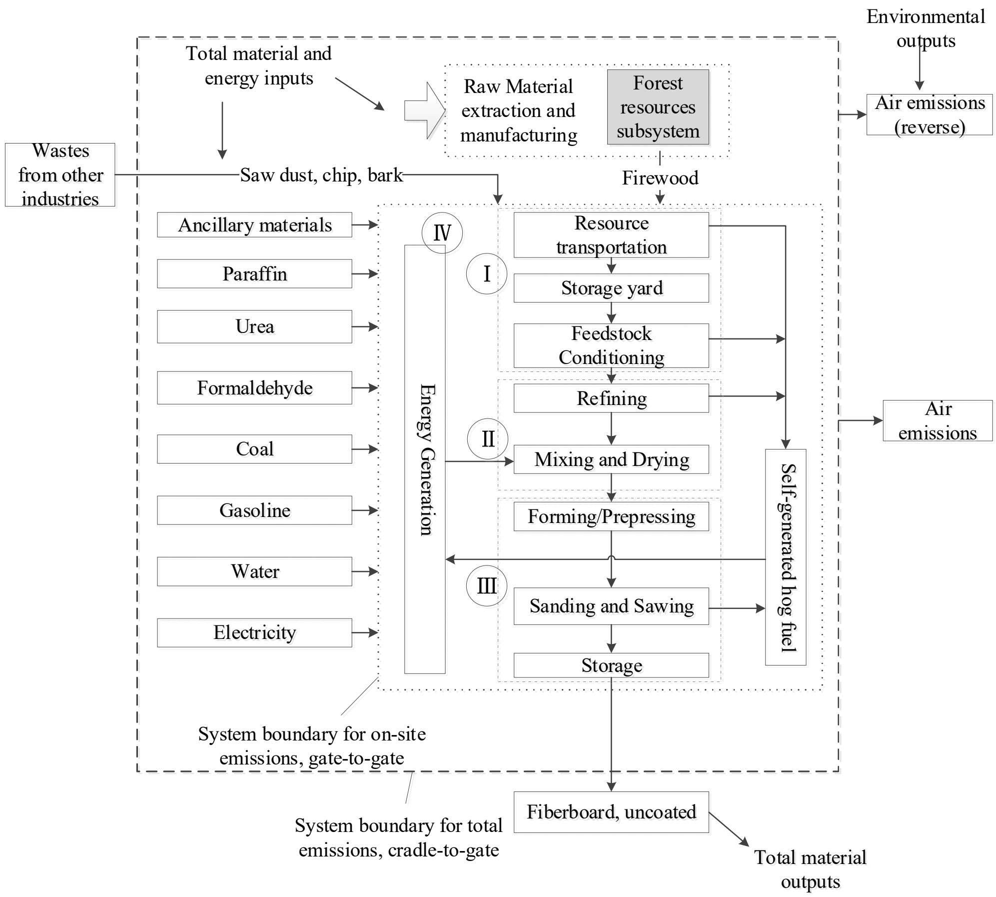

Figure 1. System boundaries of the complex forestry enterprise under assessment. Source: Authors.

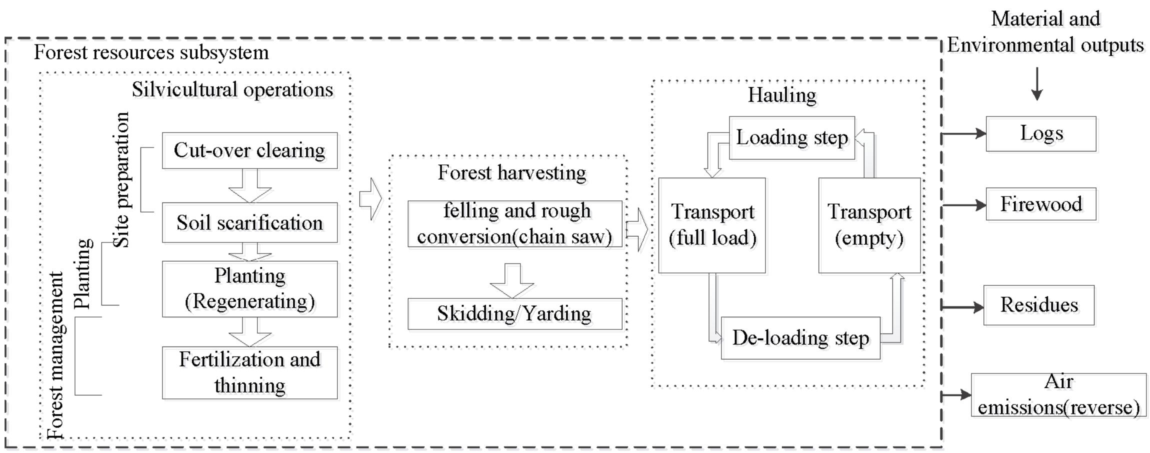

Figure 2. Processes of the forestry resource subsystem. Source: Authors.

2.5. Biogenic Carbon

2.5.1. Calculation Principle

When assessing the environmental impacts of forest products, a clear distinction should be made between biogenic carbon and fossil carbon. For the impacts of biological carbon, most studies following the 'carbon neutralization' hypothesis and considering the forest products are carbon balanced. They believe that the amount of CO_2 absorbed by forest systems from the atmosphere is equal to the amount released by forest products at the end of life. Therefore, forest products are carbon balanced, and the impact of biological carbon can be ignored [31]. There are two premises of the 'carbon neutralization' hypothesis. First, the carbon cycle here consists of the absorption of CO_2 during plant growth and the release of CO_2 during plant decay or combustion. Second, the amount and speed of carbon absorption and release in the carbon cycle of biological sources are in balance [35]. Some studies have proposed that the absorption of carbon dioxide by wood through photosynthesis must be included in the life cycle assessment of forest products if the preconditions are not met. The carbon content of biomass raw materials can be calculated through the quality and moisture content of consumed biomass raw materials. Then, the researchers should calculate the amount of CO_2 absorbed from the atmosphere for the production of one functional unit of the product according to the carbon balance principle [36].

In this study, there is little correlation between the further processing of logs produced by subsidiary A and the research objective. Meanwhile, the fiberboard products in subsidiary B are intermediate products, which are difficult to trace in the downstream and have considerable uncertainty in the final treatment [37]. Accordingly, only part of the carbon cycle is included in the boundary of the system. In terms of ways of carbon sequestration (carbon pool), the method includes aboveground biomass, underground biomass, deadwood, litter, and soil organic matter. The carbon stored in the harvested wood products is only the result of a partial transfer of sequestrated carbon in the aboveground biomass between pools [38]. Therefore, it cannot reflect the total absorption of forest (biomass carbon pool only).

With the development of low-carbon economy and the establishment of the trading market for forest carbon sinks, in terms of the forest cultivation stage, the forest carbon sink owned and managed by the enterprise itself (the capacity of the forest to absorb and store CO_2) can be regarded as an effective way to reduce the greenhouse effect. It can reflect the degree of the enterprise to fulfill its social responsibility and sustainable development [39]. At the same time, from the perspective of enterprises, the cultivation of forest resources is not only a production process (obtaining harvested wood), but also a method of creating and protecting the ecological environment through forests. The capacity and quantity for absorbing CO_2 of forest area are affected by tree species, forest age, natural conditions, and even the level of management [39]. Therefore, the amount of carbon sequestration per unit output of the subsidiary A in the forest cultivation stage was calculated using the forest carbon sink methodology, and was included in the life cycle impact assessment process.

2.5.2. Models and Approach

At present, there are two kinds of methods to measure the physical quantities of carbon sinks. One is the method of sample plot inventory, which is closely related to the calculation of biomass [40]. The other is the method based on the principle of micro-meteorology. However, it is difficult to employ the latter for measurement in practice, which can be attributed to the special measuring instrument used in large areas [41]. As a result, the first method has been widely used in China [42]. The methods of sample plot inventory are comprised of three subdivisions. The first is the biomass method, which is based on forest biomass data and converted by the proportion of plant dry-weight carbon. It is the most commonly used method for forest carbon sink measurement [42,43]. The second is the volume method, which is based on forest volume data. Although it can be considered as an extension of the biomass method, there is no substantive breakthrough. The third is the biomass inventory method, which is based on the relationship between biomass and volume, and has the advantages of simple operation and high precision. On the basis of the above methods, there are a variety of documents for us to guide carbon sink measurement that have been issued by various countries and institutions.

Referring to the relevant methods recorded in China's "Guidelines on Carbon Accounting and Monitoring for Forestation Project 2014", one of the national forestry standards, this study calculates the total physical amount of carbon sink of the forest managed by subsidiary A and the carbon sequestration amount per unit of output based on the data of forest resource archives of the case enterprise. In this study, only the change of carbon pool on biomass is considered. In contrast, the shift in carbon pool on dead organic matter and soil is not considered.

Forest biomass carbon reserves are calculated according to Equation (1).

$$C_{TREE,i,j,t} = \frac{44}{12} \times \sum_{j=1} (B_{TREE,i,j,t} \times CF_{TREE,j}) \tag{1}$$

$C_{TREE,\,i,\,j,\,t}$ is the biomass carbon storage (in t) of tree species j in the carbon layer i of the year t. $B_{TREE,\,i,\,j,t}$ is the biomass (in td m) of tree species j in carbon layer i at year t. $CF_{TREE,\,j}$ is the biomass carbon content (in kg C· (td m)$^{-1}$) of tree species j. In addition, 44 and 12 are the relative molecular mass values of CO_2 and C, respectively.

The biomass equation method is preferred for the calculation of forest biomass, shown in Equation (2).

$$B_{TREE,i,j,t} = f_j(x1_{i,j,t}, x2_{i,j,t}, x3_{i,j,t}, \cdots,) \times N_{TREE,i,j,t} \times A_{i,t} \tag{2}$$

$B_{TREE,\,i,\,j,\,t}$ is the biomass (in t) of species j in carbon layer i at year t, and $f_j\,(x1_{i,\,j,\,t},\ x2_{i,\,j,\,t},\ x3_{i,\,j,\,t},\ \ldots)$ represents the allometric equation (in td m p-1) of species j in year t. $N_{TREE,\,i,\,j,\,t}$ is the number (in p·Ha^{-1}) of tree species j in the carbon layer i of the year t. $A_{i,\,t}$ is the land area (in Ha) of the carbon layer i in year t.

In general, studies on carbon sequestration of harvested wood focus mostly on a national macro-level [38] or on the perspective of carbon balance for the product [7]. This study focuses on the carbon sequestration of the forest managed by subsidiary A to produce wood-based products (logs, cutting residues, firewood, etc.) from the perspective of enterprises. Harvested wood products (excluding residues and other substances left in the forest) can be regarded as the same wood-based biomass [38] used in the production of downstream products. From the perspective of wood-based biomass, this study tries to set up a proportion relationship between logs, cutting residues, firewood, and living trees through volume relationships to calculate the forest carbon sink apportioned to unit output.

The amount of CO_2 absorbed by the annual output (forest products in biomass) of the enterprise is evaluated according to Equation (3):

$$C_{C_i,t} = \frac{V_{RL,i,t}+V_{r,i,t}}{V_{T,i,t}} \times \sum C_{TREE,i,j,t} \tag{3}$$

$C_{Ci,\,t}$ refers to the amount of CO_2 (in t) absorbed by the annual output at year t of complex forestry enterprise i. $V_{RL,\,i,\,t}$ refers to the volume of logs at year t of enterprise i (in m^3). $V_{r,\,i,\,t}$ refers to the volume of the rest of the products other than logs (cutting residues, firewood). $V_{T,\,I,\,t}$ refers to total stand volume at year t of enterprise i. $\sum C_{TREE,\,I,\,j,\,t}$ refers to the summary of $C_{TREE,\,i,\,j,\,t}$. The values of j are Chinese fir and Masson Pine, respectively.

Table 2 shows the models and relevant parameters. This study only focuses on the arbor forest rather than economic forest species, understory vegetation, and fallout layers. The estimation of the forest carbon sink just includes the aboveground and underground parts, excluding the carbon storage in the soil.

Table 2. Models and parameters.

	Tree Species	Equation	Parameter Value	Source of References
Biomass equation	Chinese fir	$W = aD^{b*}$	a = 0.0740, b = 2.39	[44]
	Masson Pine	$W = a(D^2H)^{b*}$	a= 0.00951, b = 1.138668	[45]
	Tree species	Parameter value		Source of references
Carbon content	Chinese fir	46.97%		[46]
	Masson Pine	46.0%		[47]

*W: The total biomass of the whole tree (including the biomass underground); D: Breast diameter of trees; H: Height of trees.

3. Results and Discussion

3.1. Inventory of the Complex Forestry Enterprise

The inventory analysis of each subsystem in this study processes not only the foreground data of field operation, but also the background data (i.e., the extraction of raw materials, the production and transportation of system inputs, and energy production). The foreground data are obtained directly in the enterprise through interviews with relevant personnel of the enterprise. The background data (fossil fuel, agricultural chemicals, and machinery production) are taken from the Ecoinvent database. Table 3 shows all inventory inputs and outputs for the production of 1 m^3 of biomass and 1 m^3 of MDF.

Table 3. Inventory inputs and outputs.

Category	Item	Amount	Category	Item	Amount
Outputs Ⅰ	biomass	1 m^3	Material	electricity	324.1 kWh
Material	seedling	24.94 p		diesel	1.23 L
Emission (air)	CO_2	−2.59 t		wood fuel	0.19 t
Outputs Ⅱ	MDF	1 m^3	Emission (air)	particulates Ⅰ	0.33 kg
Material	chips	0.1 t		formaldehyde Ⅰ	0.03 kg
	sawdust	0.15 t		particulates Ⅱ	0.002 kg
	bark	0 t		formaldehyde Ⅱ	0.001 kg
	fuelwood	1.61 t	Emission (liquid)	COD_{Cr}	2.524 g
	paraffin	5.84 kg		BOD_5	0.532 g
	urea	72.69 kg		SS	1.465 g
	formaldehyde	109.95 kg		ammonia nitrogen	0.076 g
	lube oil	7.82 kg		formaldehyde	0.002 g
	water	1.13 L	Noise	-	51.42 dB

Source: A questionnaire survey conducted in the case enterprise, and the reports issued by the third-party testing unit entrusted by the enterprise.

The inputs of the forest resource management subsystem usually include seedlings, energy used for forest management as well as production and transportation of fertilizer and pesticide, fertilizer, herbicide, and pesticide used during stand growth, and fuel and lubricating oil needed to provide power and maintenance equipment for thinning and harvesting operation [48]. According to the field survey, subsidiary A neither uses pesticides (to pass the forest certification) nor thinning. Generally, the outputs of forest resource management subsystems are mainly logs, cutting residues, firewood and waste discharged to air, water (groundwater and water surface), and soil. Here, cutting residues are referred to as the treetops, branches, and small-diameter timber left when harvesting. The three disposal scenarios for these residues are: (1) Left to rot in situ; (2) stacked and burned in the forest depots; (3) transferred to downstream as a follow-up processing step. The material transferred will generally be included in the life cycle calculation as a by-product [49]. The cutting residues of subsidiary A are mainly collected and transported to the downstream (subsidiary B). According to the company's forest resource files, the forest land managed by subsidiary A is quite scattered. Meanwhile, the position of the forest land that the government allows to cut is under change each year. The residues left on the site may have an impact on the nutrient cycle of the soil [26], which is difficult to be measured directly. Therefore, in the study of LCA, the nutrient flow is usually not considered [48].

In subsidiary B, a certain proportion (10% in this case) of the raw materials consumed by the wood fuel boiler comes from the waste generated in the production process of several workshops of the enterprise. Recycling materials with unchanged properties shall not be listed or distributed with the environmental load [26]. The emission information can be obtained from the reports issued by a third-party testing unit entrusted by the enterprise.

3.2. Life Cycle Impact Assessment of the Complex Forestry Enterprise

The software used in the LCA modeling process is Simapro 8.5. The results are computed using the impact 2002+ method [49]. The method integrates the problem-oriented mid-point method (CML) and the result-oriented damage type method (Eco-indicator 99) through coordination and collocation. The mid-point is defined as a parameter in a cause–effect chain or network for a particular impact category that is between the inventory data and the category end-points. The damage type method reflects differences between stressors at an end-point in a cause–effect chain and may be of direct relevance to society's under-standing of the final effect [50]. There are fifteen impact indicators of the mid-point categories: Carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acid/nutrients, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, and mineral extraction. The further steps of the impact 2002+ method allocate these mid-point indicators to one or more damage indicators, the latter representing quality changes of the environment.

Figure 3 shows the results of the relative characteristic values of the mid-point indicators. It is essential to know that impacts on climate change of forest operation processes are negative, which means that a positive effect on global warming is obtained. However, this process has a certain impact on terrestrial eco-toxicity (13.6%) and soil acidification (2.76%) because of the application of fertilizers or pesticides during the seedling production. A high percentage (98.3%, 98.8%) of carcinogen impacts and non-carcinogen impacts are mostly attributed to the boiler. Specifically, it is an adverse effect on human health caused by the gas emissions that emerged by the combustion of wood fuel boilers. The stage of fiber preparation is the primary contributor to other impacts. The proportion of the contribution of fiber preparation to land occupation impacts and mineral extraction impacts is up to 98.9% and 99.9%. In contrast, the percentage of contribution to climate change impacts is much lower (38.2%).

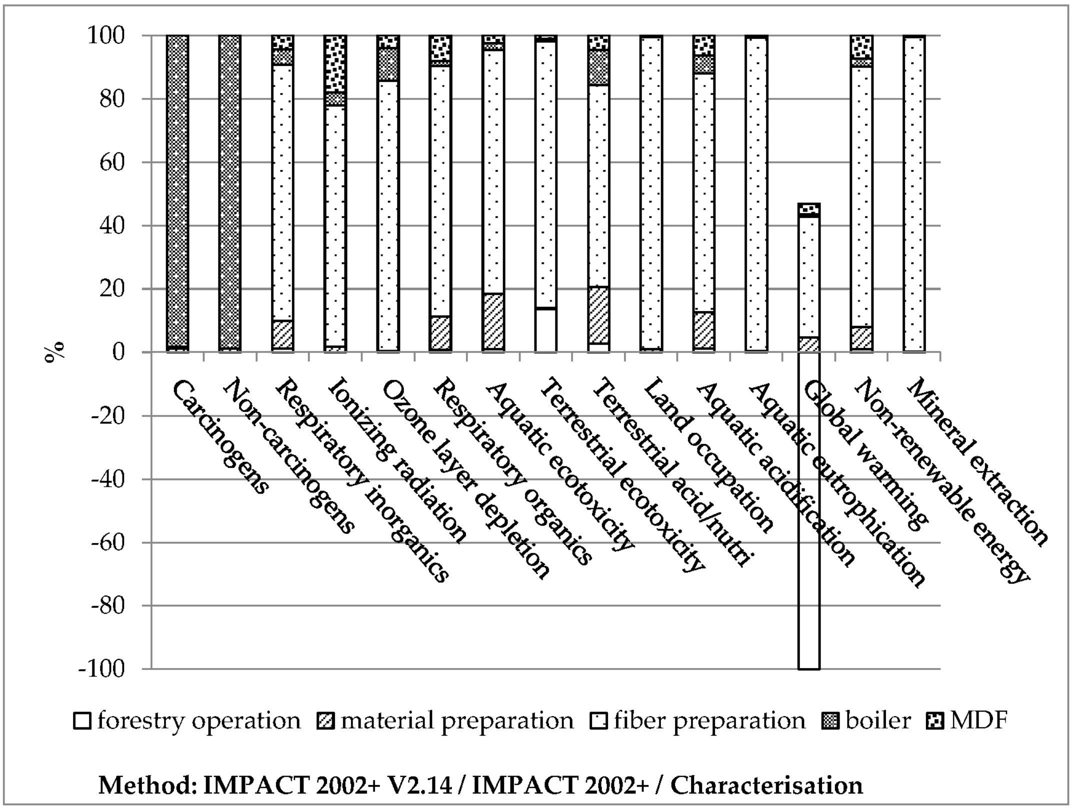

Figure 3. Relative characteristic values of mid-point indicators (the year 2018).

Figure 4 shows the results of the relative characteristic values of damage indicators. The stage of energy regeneration is the main contributor to human health impacts (97.4%), while this percentage of the MDF stage is almost 0%. The stage of fiber preparation accounts for 81.5% and 82.3% of ecosystem quality impacts and resource impacts. Simultaneously, the contribution of the forest operation stage to ecosystem quality impacts is 10.6%, and the contribution of the MDF stage to resource consumption is 10.6%. It is notable that the impacts of the carbon sink from forest production and management in the forestry operation stage have a positive impact on climate change. In contrast, other stages contribute a different proportion of detrimental impact, of which the proportion of the MDF stage is 38.2%.

Furthermore, substances affecting the environment of hotspots are recognized through the contribution analysis separated for each stage (Figures 5–8). The unwanted effects of the forest operation stage are mainly due to the harvesting, transportation, and use of oil, while the beneficial effects originated from the absorption of CO_2 by tree growth in the cultivation. The most significant contributor to the environmental impacts in the material preparation stage of the fiberboard production is the fuelwood, which includes uses as raw materials and fuel. Other substances, including fossil fuels (such as oil and coal consumed in transportation) and power consumption, also impact the environment.

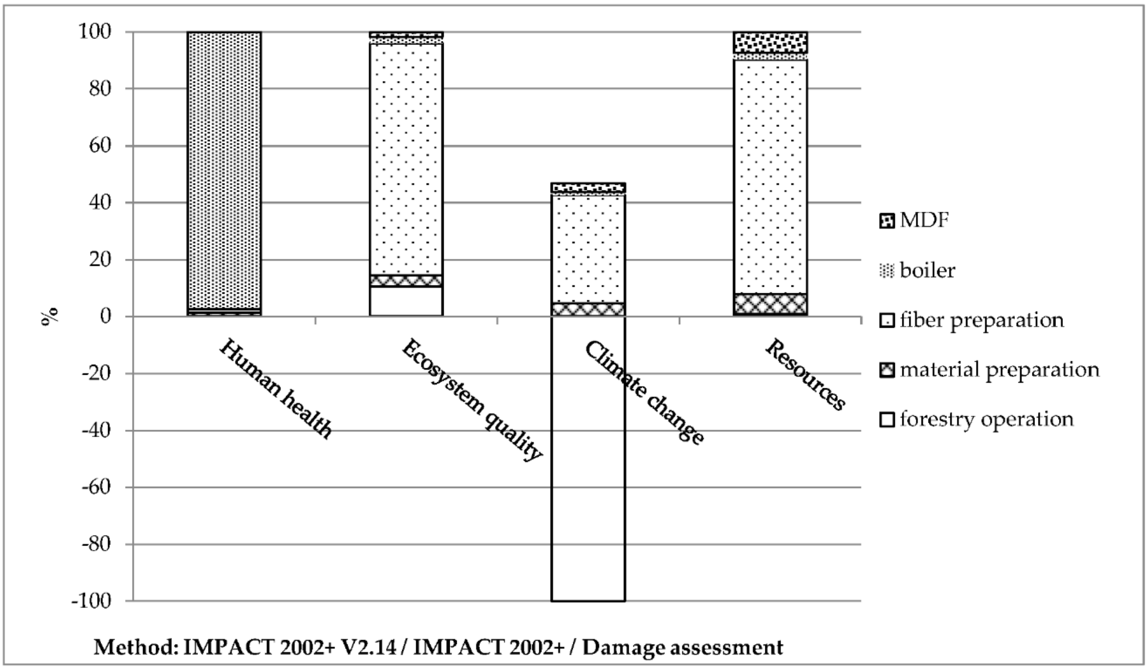

Figure 4. Relative characteristic values of damage indicators (the year 2018).

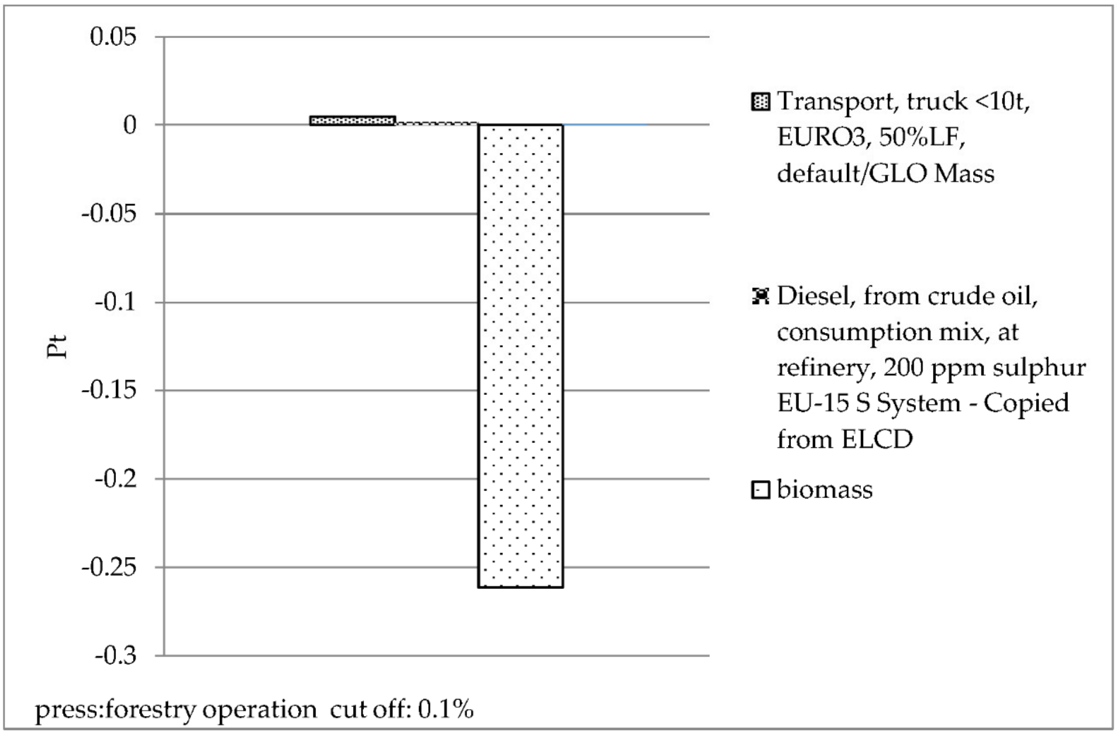

Figure 5. Contribution analysis of the forestry operation stage.

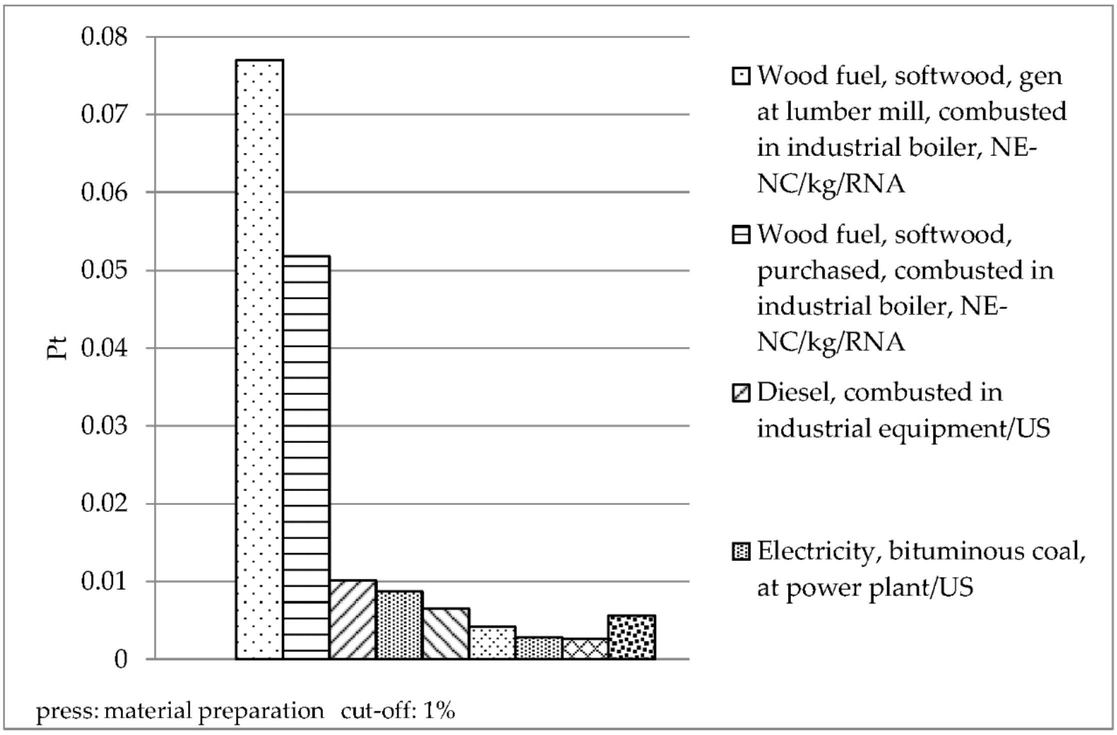

Figure 6. Contribution analysis of the material preparation stage.

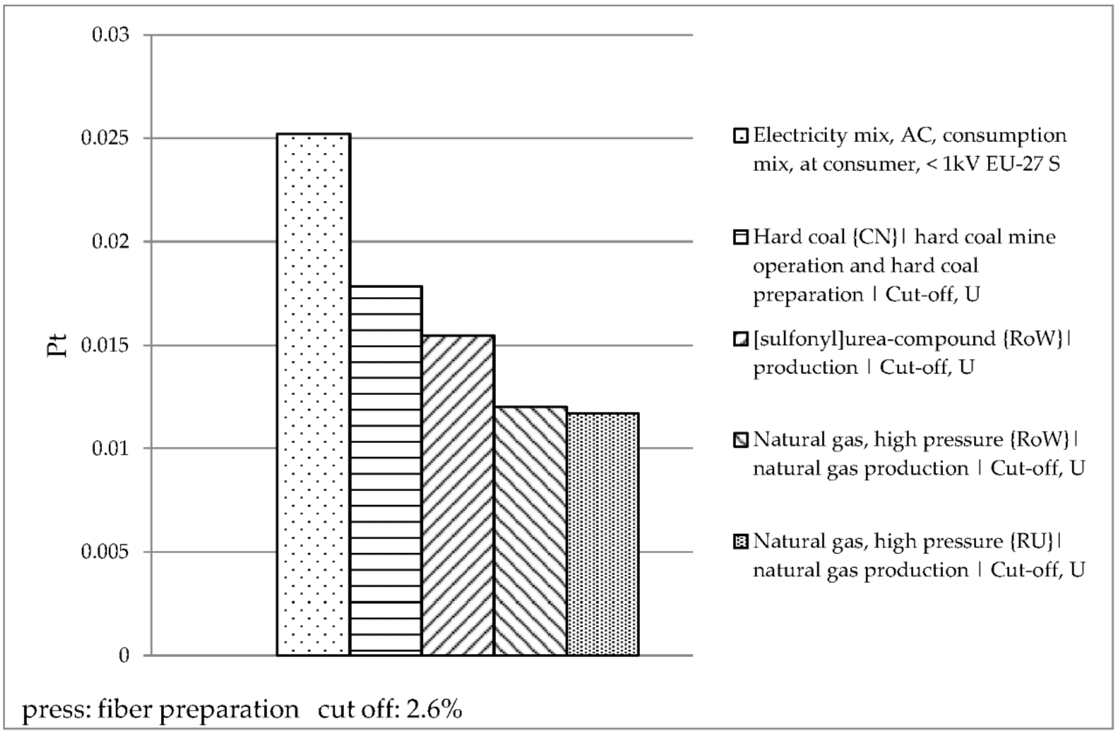

Figure 7. Contribution analysis of the fiber preparation stage.

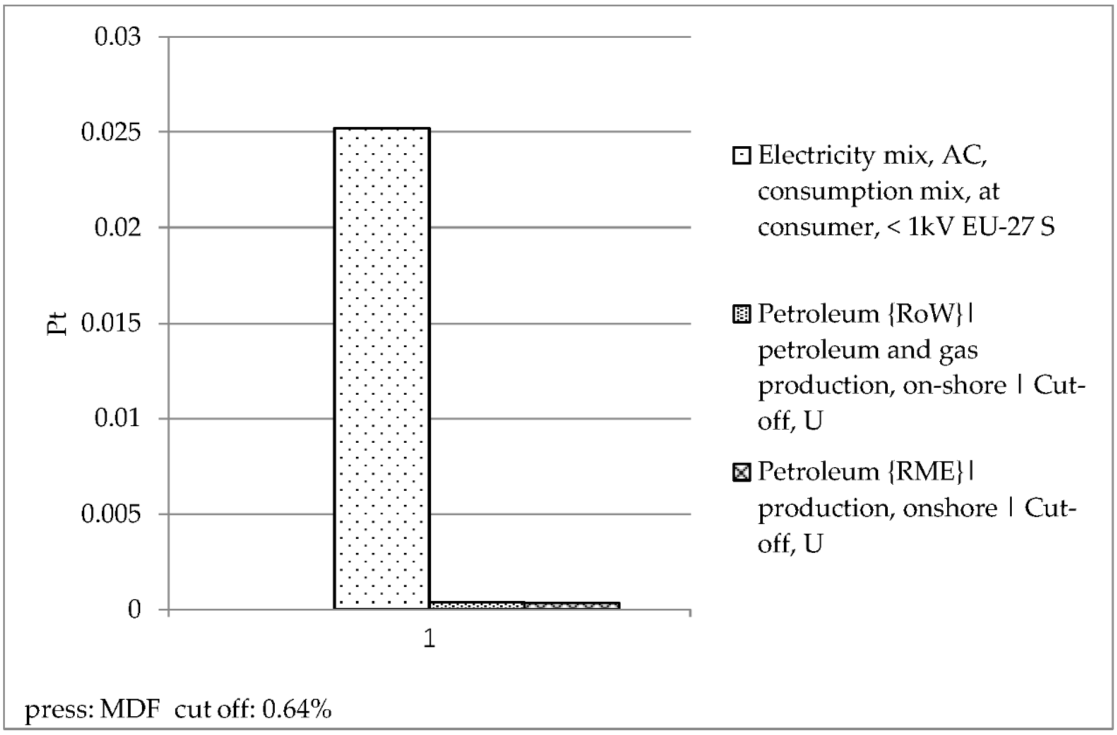

Figure 8. Contribution analysis of the medium-density fiberboard (MDF) stage.

3.3. Proposals for Environmental Improvements

At the stage of forest cultivation, fertilizers are a very important source of nutrition to ensure the quality and speed of seedling growth. In order to reduce the detrimental impact on the environment of the fertilizers used in seedling production, the types of fertilizers and the modes that are applied may be changed accordingly. As far as the selection of the fertilizer type is concerned, compound microbial fertilizer can be used. Compound microbial fertilizer is a kind of non-toxic and pollution-free biological fertilizer that is fermented by one or several beneficial microbial bacteria [51]. It has been widely used in a variety of crops and has been introduced into the field of seedlings in recent years [52]. The compound microbial fertilizer is environmentally friendly with a higher fertilizer effect, and can activate the soil's microbial ecological environment [53]. Under the conditions of farmland, compound microbial fertilizer can save 50% of chemical fertilizer without reducing the yield of crops [54]. In addition, for seedlings grown in containers, controlled-release fertilizers can be used. Controlled-release fertilizer has the advantages of long fertilizer effect, less dosage (10% to 20% less than conventional fertilization), low cost, non-toxicity, degradability, safe application, no pollution, and increased production and income [55]. We can also change the method of root fertilization to foliar fertilization. Foliar fertilization not only has cost advantages, but also avoids soil contamination [56]. Due to the complexity of the factors that affect the CO_2 absorption capacity of the forest, this study does not make any suggestion in this aspect.

Alternative scenarios were established on the strength of sensitivity analysis for the stage of fiberboard production. The actions to reduce the environmental impacts were proposed along with the management team of subsidiary B during this case study execution, with a focus on reducing inefficiencies and changing the thermal plant technology.

1) Changes to electric power consumption

Sensitivity analyses were conducted in four different possible situations: S0—original scenario analyzed in this study (324.1 kWh); S1—reduced electric power consumption by 3%; S2—reduced electric power consumption by 5%; S3—reduced electric power consumption by 10%. Reducing energy consumption can be achieved by improving the efficiency of the process, especially in the process of refining, drying, and pressing. The industry under study proposes the considered variations of electric energy consumption, and the results are presented in Figure 9.

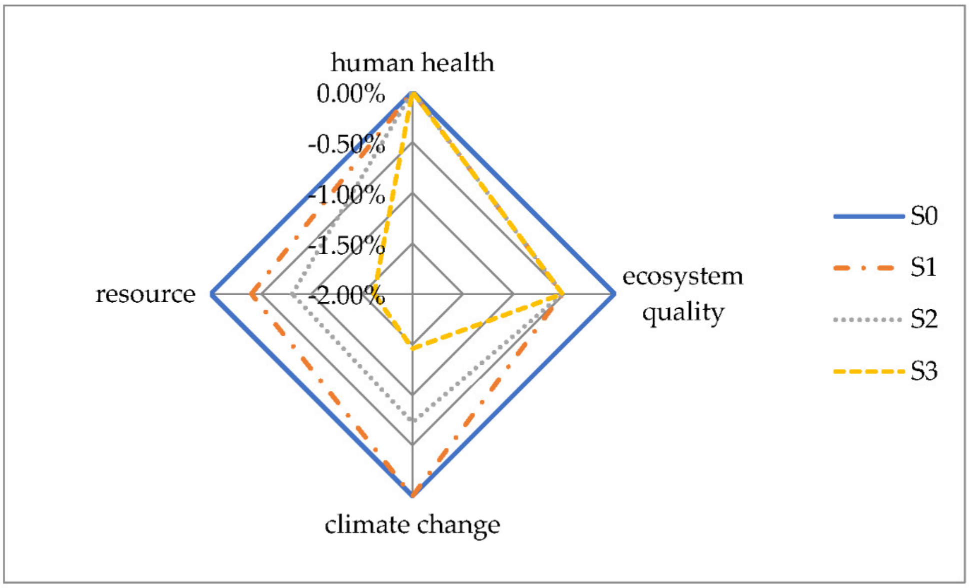

Figure 9. Sensitivity analysis for changing the electric power consumption.

Reducing electric power consumption can improve the current conditions of resource consumption, climate change, and human health. In general, the high reduction of electric power can result in a decrease in environmental impacts. The most prominent scenario is S3, especially for the categories of climate change and resource consumption. With the increase in the proportion of reduction, climate change impacts and resource consumption impacts are reduced correspondingly. However, the proportion of ecosystem quality reduction remains stable.

In terms of electric power consumption, the pneumatic conveying system of the cogeneration process (energy center) accounts for a considerable proportion. In general, improvements for this system may include the aspects of design and use. However, in this case, redesigning the cogeneration process is impractical and should be excluded. Therefore, the improvement suggestions in this study are for the use of equipment. Firstly, we can adjust the parameters of air flow, which mainly include speed and mixing concentration of air flow. Too fast of a delivery speed or too large of an air flow will result in a large increase in power consumption. In addition, for conveying a certain amount of material, low mixing concentration means that more gas flow is consumed. It is necessary to adjust the parameters by considering the type of material inputs. At the same time, some equipment often idles due to pipeline blockage, poor discharge, and low separation efficiency. Therefore, the maintenance of equipment in use is also an effective way to improve the power efficiency.

2) Changes to fuel wood consumption

Fuelwood is defined as a hotspot for two main reasons. The first is the emission generated during the combustion of fuelwood in the boiler, and the second is the use of fuelwood as raw material. The proposed actions are simulated through four scenarios: S0—original scenario analyzed in this study (1.8 t); S1—reduced wood consumption by 3%; S2—reduced wood consumption by 5%; S3—reduced wood consumption by 10%. The three alternative scenarios are built by the company within this study.

The results showed that reducing wood consumption will undoubtedly bring in environmental benefits, mainly to prevent climate change and resource impacts (Figure 10). Reducing the original wood consumption (100%) to 90% can result in a reduction of impacts in the cradle to gate (C-G) life cycle by 0.52% for ecosystem quality, 1.46% for climate change, and 1.62% for resource consumption.

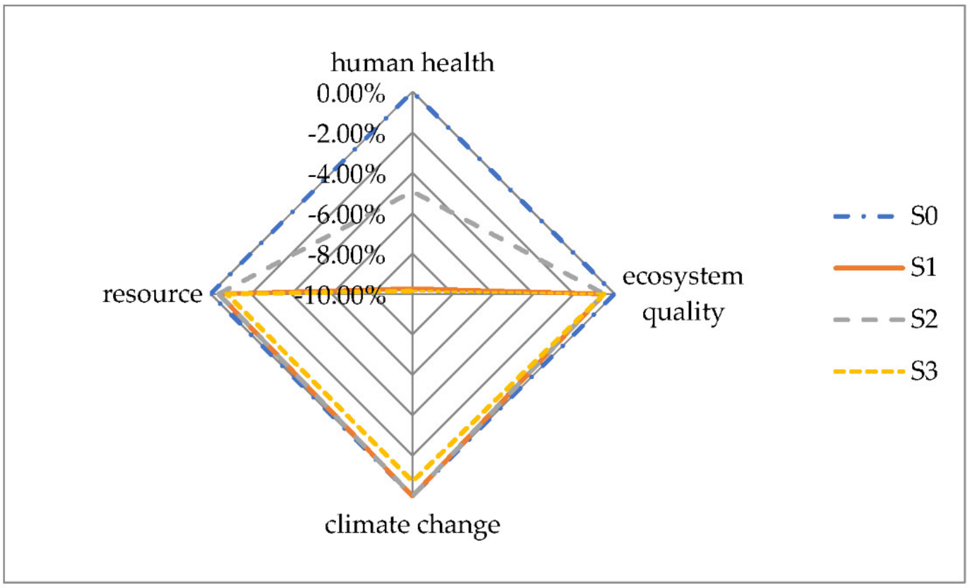

Figure 10. Sensitivity analysis for changing the fuelwood consumption.

Therefore, two methods are to be proposed to improve environmental performance. One is to enhance the technology of the energy center and to improve the combustion efficiency of the boiler. The other is to improve fiberboard production technology with other materials as substitutes for wood (e.g., wheat straw, flaxseed straw, awn grass, boxwood, marijuana, and other crops).

The energy center is a high-efficiency, energy-saving, and environmentally friendly heat energy supply system. It uses the waste generated in the process of wood-based panel production, including bark, sawdust, sanding powder, etc. Hot oil and steam are the main products in this system and can act as the main heating sources of fiberboard. During the production, sanding powder comes out in the largest amount as the wood-waste. In general, it can be burned for heating, or put into a drying pipeline for fiberboard production. However, the mix of sanding powder will inevitably affect the product performance. Sanding powder cannot be fully used because of its characteristics of adhesion, explosiveness, and inconvenient collection and treatment. Making the sanding powder into granular fuel is not only a practicable method to improve the combustion efficiency and avoid the hidden danger of the traditional combustion mode, but also saves costs and even increases revenue for enterprises.

4. Conclusions

For this study, an LCA of complex forestry enterprises was conducted in a 'forest–board integration' company in South China. This paper can provide a new perspective and can be used to carry out environmental management efficiently for complex forestry enterprises. The production and management of complex forestry enterprises often cover several links in the value chain of forest products. Therefore, the environmental impact assessment also involves the life cycle of various products. This study includes the absorption of CO_2 by trees in forest cultivation activities in the impact assessment. This study is carried out with the LCA analysis by multifunctional units. In this sense, a comprehensive and scientific life cycle assessment of complex forestry enterprises has been achieved.

The LCA results, hotspots, and main substances affecting the environment were identified and used as a reference to create proposals of alternatives in order to improve the environment profiles of complex forestry enterprises. These hotspots and substances include the carbon sequestration and seedlings of forest operations, electric power of fiber preparation, and fuelwood of boilers. For this, the impact 2002+ method was adopted, and the results showed that changing manufacturing processes and technology can yield overall gains in different impact categories. Fifteen mid-point indicators and four damage indicators were calculated, taking into account carbon sinks. Improvement suggestions are put forward from three aspects: Changing the type and applied method of fertilizer, reducing electric power consumption, and reducing fuelwood consumption.

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