Environmental Impact Assessment of Wood Pulp from a Eucalyptus Plantation in South China by Using Life-Cycle Analysis

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Abstract

This exploratory study evaluated the environmental impacts associated with Bleached Eucalyptus Kraft Pulp supplied from a eucalyptus plantation in South China by applying the life-cycle analysis approach. The system boundary was defined by a ''cradle-to-gate'' perspective including the forest subsystem and the pulp mill subsystem. Key processes were investigated and site-specific data were collected during 2009 and 2010 through field trips to a leading plantation operator and a representative pulp mill in China. Umberto 5.5 software was used to conduct a life-cycle inventory, which compiled all the inputs and outputs of the examined system. Hot-spot processes with high environmental burdens were identified with regard to selected impact categories of global warming, acidification, eutrophication, nonrenewable resources depletion, and human toxicity.

According to the findings of this study, the forest subsystem showed significant contributions to the total environmental burdens in almost all impact categories, mainly due to the application of fertilizers in eucalyptus plantation management. The study discovered that while the pulp mill subsystem was the primary contributor to global warming impacts, the upstream processes of raw materials and energy production accounted for more than half of the impacts of acidification, human toxicity, and resources depletion. Therefore, eucalyptus plantation management and the supply of raw materials and energy in pulp mills in China are concluded to be concerns for future development. These findings may help the Chinese forest industry and pulp industry achieve better environmental performance toward sustainable development.

In recent years, China has become one of the largest pulp and paper producers in the world (He and Barr 2004, Yang et al. 2006). According to the statistics of the Chinese Paper Association (CPA),[1] China's pulp and paper industry created an annual production of over 92.7 million tons of paper products in 2010, with more than 3,700 manufacturing enterprises offering over 737,300 employment opportunities (CPA 2011).

Raw material supply has been a crucial challenge for the sustainable development of the Chinese pulp and paper industry. For manufacturing pulp and paper products, fiber furnish comes from either domestic supplied or imported virgin wood pulp, nonwood fibers, and recycled paper (Chinese Academy of Forestry 2007, CPA 2010).

With the rapid economic growth in China, the demand for wood pulp in China's market over the past decades has experienced steady growth, and the most favorable grade among all wood pulps is Bleached Eucalyptus Kraft Pulp (BEKP; Barr and Cossalter 2004, He and Barr 2004, Zhu et al. 2004, Pöyry Forest Industry 2007). Since 2001, there has been a remarkable development of China's wood pulp industry. This development of wood pulp mills has been integrated with the establishment of plantations as the pulpwood supply base. China's total acreage of existing plantations reached 61.69 million hectares by 2008 according to the seventh forest resources inventory, of

[1] The Chinese Paper Association is the authority in the Chinese paper industry, acting as a linkage between the government and industry. The association is responsible for information collection and publication of statistics.

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which a total of 5.9 million hectares were for pulpwood use. South China is the leading region for the establishment of large-capacity pulp mills fed by plantations of mostly eucalyptus (China National Development and Reform Commission 2005, China State Forestry Administration 2010).

The activities of intensively managed eucalyptus plantations cover a large variety of practices such as breeding, land occupation, fertilizing, and clear-cut harvesting. This leads to increasing concerns for how to manage plantations in a sustainable way. Industrial production of pulp is also raising concerns due to resources and energy consumption and emissions generated in the pulp mill.

Life-cycle analysis (LCA) methodology is a well-established technique for evaluating the environmental impacts associated with the life cycle of a product or a system (Guinee et al. 2001, International Organization for Standardization [ISO] 2006). LCA has been proven to be a useful tool for environmental considerations toward sustainability, and it has been applied in many international studies for impact assessment of pulp and paper products (Dias et al. 2006, 2007; Jawjit et al. 2006; Gaudreault et al. 2007a, 2007b; Gonzalez-Garcia et al. 2009).

To the best of our knowledge, the LCA approach has not been applied for pulp product analysis in China. The aim of this exploratory study was to evaluate the environmental impacts associated with BEKP supplied from eucalyptus plantations in south China, using LCA as an analytical tool.

Methodology and Materials

LCA is a systematic tool to describe the full resource usages and environmental impacts associated with supply chains delivering products or services (Organisation for Economic Co-operation and Development [OECD] 1998, Arena et al. 2004). In this study, the environmental impacts associated with the eucalyptus plantation–based wood pulp produced in China were evaluated by using the LCA approach. This study was composed of four sequenced phases following ISO Standard 14040: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 2006).

Goal and scope definition

This study aimed to analyze and quantify the environmental impacts associated with the production of BEKP in China, which is supplied by large-scale eucalyptus plantations. It also aimed to identify the hot-spot processes within the life cycle that contribute greatly to environmental burdens.

Functional unit.—In this study, the function of the examined system was to deliver Kraft eucalyptus pulp from eucalyptus plantations to domestic markets in China. In order to make the results of this study comparable to existing international studies, 1 air-dried ton (ADT) of BEKP with 10 percent moisture content ready at the pulp mill gate was defined as the functional unit.

System boundary.—The system boundary of this study adopted the ‘‘cradle-to-gate’’ perspective, and the system was restricted to the selected life-cycle stages of raw material extraction from the eucalyptus plantation, passing through logistics activities and pulp manufacture processes, to the final products of market pulp ready at the pulp mill gate. The examined system (see Fig. 1) was separated into two subsystems for better description and data collection, including the forest subsystem and the pulp mill subsystem.

For the forest subsystem, eucalyptus timber from a plantation was considered the fiber material source for pulp manufacture in this study. A leading eucalyptus plantation operator located in Guangxi supplying logs for pulpwood was selected as the case study. The forest subsystem covered all the activities involved in eucalyptus plantation management in South China, including seedling breeding in an industrialized nursery; seedling transport from nursery to plantation sites with an assumed average distance of 80 km; silviculture operations of site preparation, fertilization, planting, and tending; harvesting operations; and log transportation from harvest stands to the pulp mill gate with an assumed average distance of 220 km.

The company used a fertilization regime including the application of base fertilizers and follow-up fertilizers with

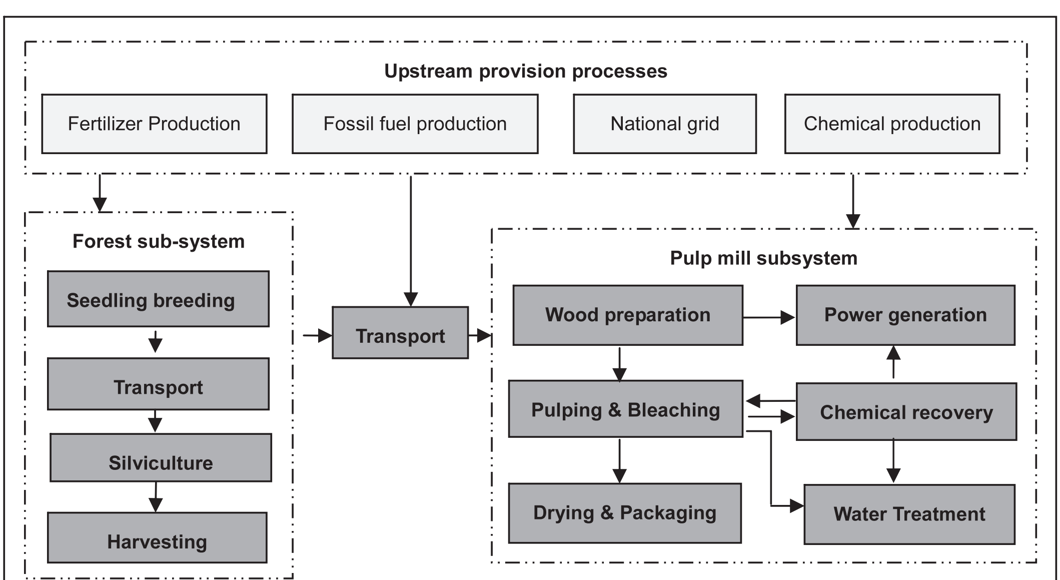

Figure 1.—Schematic overview of the examined system boundary.

site-specific prescription based on local site conditions. An investigated prescription from the company was applied in the estimation of fertilizer consumption. A mixture of 150 g of nitrogen-phosphorus-potassium (N-P-K; 15-15-15) fertilizer and 200 g of calcium-magnesium-phosphorus (CMP) fertilizer is given for each stem as base fertilizer prior to planting. Follow-up fertilization with 400 g of N-P-K (15-15-15) fertilizer per stem was applied three times, at 2, 12, and 24 months after plantation was established. Fertilization operations are labor-intensive and were carried out manually by contract workers.

For the pulp mill subsystem, a Kraft pulp mill with an annual capacity of 400,000 tons of pulp in Hunan province was considered a representative manufacturer with ''state of the art'' technology in producing BEKP, and it was selected as the case study.

The pulp mill subsystem accounted for all on-site processes related to pulp production in the pulp mill, including wood handling activities (loading, debarking, chipping), pulping and bleaching processes (cooking taking place in a continuous digester, oxygen delignification, elemental chlorine-free bleaching process), and drying and packing activities (washing, formatting, drying process, packaging) until the final product of market pulp with 10 percent moisture content was ready at the storage warehouse in the pulp mill.

Apart from the major manufacture processes involved in pulp production, the on-site energy generation, chemical recovery, and wastewater treatment were also included in the analysis. The mill has a combined heat and power plant (CHP plant), including two bark boilers fed by eucalyptus bark from the debarking process and one recovery furnace fed by concentrated black liquor from the cooking process. Only a small amount of fossil fuel is consumed as supplementary fuel in these combustion devices. Supported with the on-site power generation plant, the mill is an energy-sufficient system. It not only provides the major manufacture processes with enough electricity and steam, but also generates an additional electricity surplus sold to the national grid (see energy balance in Table 1). Different processes in the pulp mill consume a huge amount of water and generate effluents, so the on-site wastewater treatment system was included in the analysis.

According to the standard LCA procedure, all the inputs (material and energy) involved in each unit process of the examined system should be tracked backward to their upstream origins, where the primary resources are extracted directly from the environment system (Guinee 2001, European Commission–Joint Research Centre–Institute for Environment and Sustainability [EC-JRC-IES] 2010a). Therefore, the upstream processes that affect the overall system's performance were taken into consideration in this study. The major upstream processes included raw material provision of fertilizers consumed in the plantation operations, chemicals consumed in the pulp mill, and energy provision of fossil fuels and electricity consumed both in the plantation operations and in the pulp mill.

Allocation procedure.—An allocation procedure was used in this study for the multifunctional unit of power generation in the pulp mill, because there is a coproduction of electricity surplus sold to the national grid.

The corresponding outputs and inputs involved in the power generation unit were partitioned based on physical relationships to various output energy streams. Based on respective energy content of these output energy streams (see the energy balance of the CHP plant in Table 1), the materials inputs and emissions from the mill's CHP plant distributed to the exported electricity to national grid accounted for 9.1 percent of the CHP plant's total. This portion of environmental impacts was subtracted from the total environmental burdens of the examined system.

Life-cycle inventory

Life-cycle inventory (LCI) is the phase used to identify material flows along major unit processes within defined system boundaries and to summarize and quantify all the relevant inputs (raw material and energy) and outputs (product, by-product, and emissions to air, water, and soil) for each single unit process (Guinee 2001, EC-JRC-IES 2010a). In this study, the specification and quantification of a full range of inputs and outputs for each single unit process were carried out with the software Umberto version 5.5 (ifu Institut für Umweltinformatik Hamburg GmbH 2005).

Data source for major inputs and outputs along the supply chain.—In applying LCA methodology, it is essential to obtain valid data along the supply chain. If possible, precise and accurate data from respective sites and regions along the supply chain are suggested (Windsperger et al. 2002). Data used to perform this study were gathered from various sources through literature review, database searches, and personal investigation through field trips to the case study companies.

Site-specific data collected from the case study's on-site operations were preferred for the analysis. Primary inventory data describing the major raw materials and energy consumption of principal operations involved in plantation management were collected from the plantation operator in Guangxi during November and December 2009, and the

Table 1.—Summary of the energy balance in the pulp mill per air-dried ton of pulp.

	Energy input				Energy output	
Devices	Feedstock	Quantity (kg)	Heating value (MJ/kg)	Inflow (GJ)	Energy carrier	Outflow (GJ)
Bark boiler	Bark	40.04	15.5[a]	0.62	Electricity internal used	1.81
	Coal	192.85	20.92[b]	4.03	Electricity for sale	1.56
Recovery furnace	Black liquor[c]	1,623.56	13.3[a]	21.59	Steam internal used	8.44
	Diesel	3.67	42.8	0.16	Steam released	5.32
Total				26.40		17.13

[a] Suggested value taken from National Council for Air and Stream Improvement (2005).

[b] Recorded data from the mill.

[c] Calculated weight of black liquor in solid state, with assumed density of spent black liquor of 1.09 ton/m^3 and average solid content of 15 percent.

Table 2.—Summary of inputs in plantation operations per cubic meter of harvested timber.

Inputs	Value
Raw materials	
Eucalyptus seedlings	16 stems
Fertilizers	
Urea (46% N)	10.85 kg
CMP (20% P_2O_5)[a]	14.15 kg
Potassium chloride (60% K_2O)	3.97 kg
Fossil fuels	
Gasoline	0.122 kg

[a] CMP = calcium-magnesium-phosphorus.

data were representative of operation year 2009 (see Table 2). Primary data for inputs and outputs from major unit processes in the pulp mill were obtained through on-site investigation during April and June 2010, representing the operation period of the second quarter of production year 2010 (see Table 3).

The remaining data gaps were filled by average data from literature and reliable data obtained from specialized databases (e.g., Eco-invent developed by the Swiss Centre for Life Cycle Inventories). Data concerning emissions to air, soil, and water caused by the operations of fertilization and chainsaw harvesting in the forest subsystem were estimated using the well-accepted approach proposed by the Intergovernmental Panel on Climate Change (IPCC 2003, 2006). It combines the obtained on-site activity data with emission factors to quantify the emissions per unit activity. Data on emissions to the atmosphere, soil, and water generated in the pulp mill subsystem were estimated with the approach proposed by the IPCC (2006), the calculation tool by the National Council for Air and Stream Improvement (NCASI 2005), and emission factors suggested by the European Environment Agency (2006).

Specification of the upstream processes.—The LCI data of energy provision (including extraction of crude oil, coal, and natural gas and production of bunker oil, diesel, and gasoline) were taken from the study results of Yuan et al. (2006a, 2006b). Data for the provision of electricity from the Chinese national grid were taken from the study of Di et al. (2005). The LCI data of production of the consumed fertilizers (including CMP, urea, and potassium chloride) were taken from the Eco-invent database. In addition, consumed chemicals in terms of variety and quantity in the pulp mill were investigated through field trips to the studied pulp mill. The major chemicals that were specified include CaO, H_2O_2, H_2SO_4, NaOH, and $NaClO_3$. LCI data of production of these major chemicals were obtained from the Eco-invent database.

Consideration of biogenic C flows.—In the LCI, biogenic C flows, including the CO_2 uptake from the atmosphere during plant growth and the CO_2 release to the atmosphere from bark and black liquor combustion in the mill's CHP plant, were accounted for. These inventoried data were only given as a reference, but not accounted for in the environmental impact assessment of global warming potentials because these biogenic C flows were assumed to be climate neutral.

First, planted trees lead to carbon stock changes in the living biomass and the carbon pools of litter, deadwood, and organic soils (IPCC 2003). In this inventory, only the sequestered CO_2 stored in the aboveground biomass was taken into consideration. The average yield of standing volume over the designed rotation length of 6 years in managed eucalyptus plantation stands was calculated based

Table 3.—Summary of inventory data from the studied pulp mill per air-dried ton of pulp.

Inputs (more than 1% in mass of the functional unit of 1 ton of pulp)	Value	Outputs	Value
Wood fiber materials		Products	
Eucalyptus pulpwood	4.86 m^3	Market pulp	1 ton
Chemicals		Electricity sold to national grid	432.73 kwh
CaO	84.69 kg	Emissions to air[a]	
CH_3OH	2.78 kg	NO_x	2.22 kg
H_2O_2	18.06 kg	SO_2	1.64 kg
H_2SO_4	25.89 kg	Particulates	1.24 kg
$NaClO_3$	31.61 kg	TRS	0.28 kg
NaOH	33.70 kg	Waste heat[b]	5.32 GJ
On-site recovered NaOH[c]	456.53 kg	Emissions to water[d]	
Energy and fossil fuels		COD	6.49 kg
Bunker oil	38.81 kg	BOD	1.89 kg
Coal	192.85 kg	Total N	0.10 kg
Diesel	3.67 kg	Total P	0.01 kg
Electricity from national grid	8.00 kWh	TSS	1.06 kg
On-site generated electricity[e]	502.63 kWh	Effluent	39.05 m^3
Internal used steam[e]	8.44 GJ	Solid wastes	
Other materials		Ash and dust	65.72 kg
Water	35.79 m^3	Sludge	39.05 kg

[a] Calculated number based on the recorded data from the mill's bark boiler, recovery furnace, and lime kiln. TRS = total reduced sulfur.
[b] Calculated number by subtracting the total generated steam with internal used amount.
[c] From the mill's chemical recovery unit.
[d] Calculated number based on the recorded data from the mill's water treatment plant after effluent treatment. COD = chemical oxygen demand; BOD = biochemical oxygen demand; TSS = total suspended solids.
[e] From the mill's combined heat and power plant.

on locally derived yield curves. Carbon sequestration in all living biomass was estimated by applying the biomass expansion factor value for eucalyptus suggested by Fang et al. (2001), which converts timber volume to mass and accounts for the noncommercial parts of branches and leaves in total biomass calculation. It was calculated that a total of 560.74 tons of CO_2 per hectare was sequestrated over one rotation in managed eucalyptus plantations.

Second, the released CO_2 from biomass fuels of bark and black liquor combustion was estimated by multiplying the consumed biomass fuels with corresponding emission factors given in the NCASI spreadsheet tool (2005). It was calculated that the biomass-derived CO_2 emission from fuel combustion reached up to 2.10 tons per ADT of manufactured wood pulp.

Impact assessment

Life-cycle impact assessment (LCIA), as defined in the ''ILCD Handbook'' (EC-JRC-IES 2010b) is the phase in which inputs and outputs of elementary flows that have been compiled and reported in the inventory are translated into impact indicator results associated with selected impact categories.

In this study, five impact categories relevant to the defined study objective were taken into consideration, including global warming, acidification, eutrophication, nonrenewable resources depletion, and human toxicity. The inventory indicators and the examined parameters assigned to each impact category are shown in Table 4. In this study, the best available characterization factors were applied in the characterization step for aggregation of the inventions contribution within each category. The applied characterization factors for contribution aggregation of the examined substances within each category examined substances were taken from the CML-IA data set version 3.9 (Institute of Environmental Sciences [CML] 2010).

Results

The overall environmental impacts associated with 1 ADT market pulp from the five selected categories are presented in Table 5.

Table 4.—Inventory indicators and parameters for the selected impact categories.[a]

Impact categories	Indicator (unit)	Parameters
Global warming	Global warming potential (kg CO_2 eq)	CO_2, CH_4, N_2O
Acidification	Acidification potential (kg SO_2 eq)	SO_2, NO_X, NH_3, H_2S
Eutrophication	Eutrophication potential (kg PO_4^{3-} eq)	NO, NH_3, TN, TP, NO_3^-, PO_4^{3-}, COD
Nonrenewable resources depletion	Energy content (MJ)	Crude oil, coal, natural gas
Human toxicity	Human toxicity potential (kg $C_6H_4Cl_2$ eq)	AOX, TRS, SO_2, NO_X, CO, particles

[a] Data sources: Heijungs et al. (1992), Lindfors et al. (1995), Hauschild and Wenzel (1998), Intergovernmental Panel on Climate Change (2006), and Institute of Environmental Sciences (2010). COD = chemical oxygen demand; AOX = adsorbable organic halides; TRS = total reduced sulfur.

An investigation of the major phases involved in the examined forest-pulp supply chain for each impact category was carried out. We attempted to find out the relative contribution of different phases especially of the two subsystems involved in the entire life cycle of the wood pulp production chain. The analysis results are illustrated in Figure 2.

Several other LCA studies of pulp and paper products (Dias et al. 2006, Jawjit et al. 2006, Gonzalez-Garcia et al. 2009) addressed forest activities having smaller contributions to environmental impacts compared with pulp mill operations. However, in this study, the forest subsystem was identified as a significant contributor to environmental burdens for four categories, including global warming, acidification, eutrophication, and human toxicity. It was responsible for almost 80 percent of the eutrophication affects and around 40 percent of the acidification impacts.

The pulp mill subsystem was responsible for more than half of the global warming potential of the total examined system. In addition, it was found that the transportation operations have very minor impacts on the environment in every impact category.

More importantly, the findings suggested that the largest contribution to environmental impacts was caused by the upstream processes of chemical production, fossil fuel extraction, and electricity production, accounting for more than 50 percent of the total human toxicity and resources depletions. In addition, the upstream processes were responsible for around 45 percent of the total acidification potential and 30 percent of the global warming effects.

An in-depth study for each impact category was implemented to determine the relative contribution of major processes involved in each of the subsystems. Results from this detailed analysis are illustrated in Figure 3.

Fertilization in the forest subsystem was identified as one of the major contributors to environmental burdens for four categories, including the global warming, acidification, eutrophication, and human toxicity. Other activities related to eucalyptus pulpwood production in China, such as the seedling breeding and harvesting operations, showed very minor effects with regard to the environment. This is probably due to the manner of manual work in these operations, which results in fewer environmental burdens.

The manufacturing processes of wood pulp production in the pulp mill, such as wood handling, cooking and bleaching, drying, and packaging, have very little impact on the environment since the studied pulp mill applied a closed-loop system in order to control the manufacturing processes with the best techniques available. The on-site chemical recovery system, power generation plant, and waste water treatment plant were identified as very important contributors to the total environmental impacts.

Table 5.—Results from characterization step of the impact assessment phase (per air-dried ton of pulp).

Category	Impact value	Unit
Global warming	2,075.96	kg CO_2 eq
Acidification	14.33	kg SO_2 eq
Eutrophication	5.81	kg PO_4^{3-} eq
Nonrenewable resources depletion	15,365.62	MJ
Human toxicity	14.94	kg $C_6H_4Cl_2$ eq

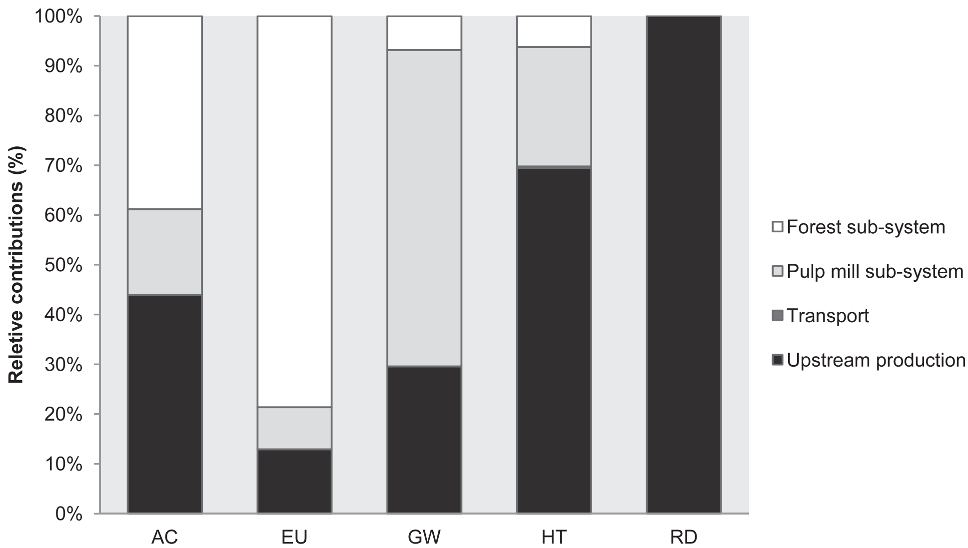

Figure 2.—Relative contributions of phases of the supply chain for each impact category. AC = acidification; EU = eutrophication; GW = global warming; HT = human toxicity; RD = resources depletion.

These findings are in agreement with Gonzalez-Garcia et al. (2009).

Global warming

Among the major processes along the entire production chain of pulp production, the unit processes of the on-site power cogeneration in the CHP plant (25%) and the wastewater treatment plant (32%) were identified as the largest sources of greenhouse gas (GHG) emissions. Fertilization operations in the plantation management were recognized as another great source of GHG emissions by contributing 7 percent of the total. In addition, the upstream processes contributed around 30 percent to the total global warming affects, as the provision processes of fossil fuel and electricity production at national grid represented a great share of the total GHG emissions.

Acidification

Fertilization was identified as one of the most prominent contributors to the total acidification impacts, and 39 percent of the acidification potential was caused by application of fertilizers. Furthermore, the upstream process of electricity provision was found to be another major

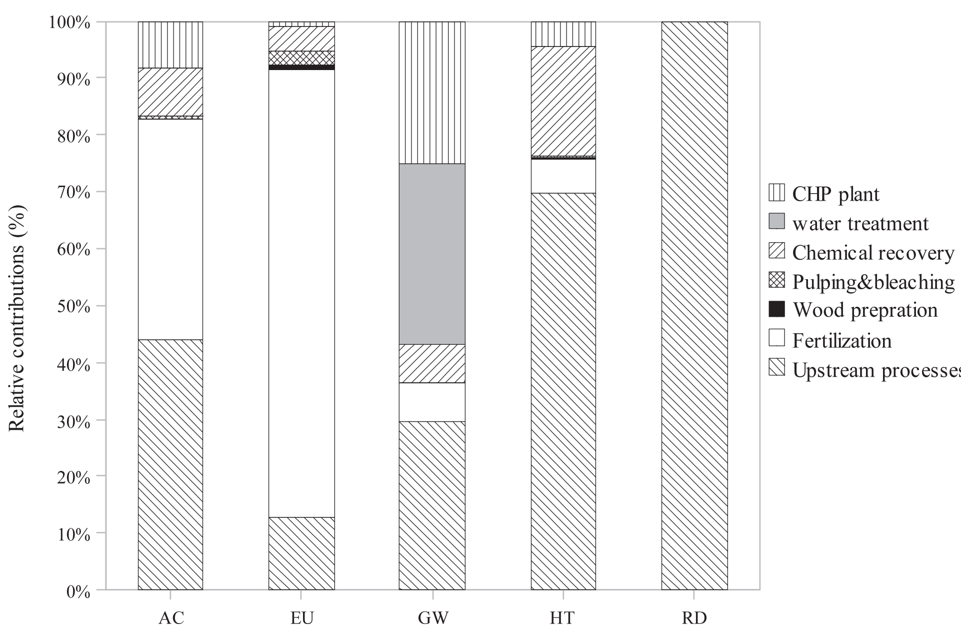

Figure 3.—Relative contributions of major processes for each impact category. Note: Impacts of the processes of drying and packaging, harvesting, seedling production, and transportation were very little and were not presented in this figure. CHP = combined heat and power; AC = acidification; EU = eutrophication; GW = global warming; HT = human toxicity; RD = resources depletion.

contribution element of acidification impacts with 43 percent of the total.

Eutrophication

As presented in Figure 3, fertilization represented 78 percent of the total eutrophicating emissions, and this was mainly attributed to the application of fertilizers in the eucalyptus plantation management. In addition, the provision processes of consumed fertilizers were identified to be another important factor to the total eutrophication impacts since these processes triggered around 7 percent of the total eutrophication emissions.

Nonrenewable resources depletion

The total nonrenewable resources depletion was distributed to the upstream processes of fossil fuel production, including the extraction of coal, crude oil, and natural gas. An in-depth analysis on fossil fuel consumption was performed in order to identify the major sources of fossil fuel consumption in the two subsystems. The results showed that the CHP plant and the chemical recovery unit in the pulp mill represented, respectively, 28 and 71 percent of the total fossil fuel depletion along the entire production chain. This was mainly due to the great quantity of bunker oil consumption in the lime kiln and the coal consumption as supplementary fuel in the bark boiler.

Human toxicity

Chemical recovery was identified as one of the major contributing factors of the human toxicity effects, because it accounted for 20 percent of the total toxic emissions. This was mainly due to the emission of toxic substances of SO_2, NO_x, CO, and particulate matter to the atmosphere. Moreover, the upstream process of electricity production at the national grid was recognized as the most important contribution (63%) of the total human toxicity impacts. This was because about 80 percent of China's power system is based on coal-powered stations, which generate a great deal of NO_x and particulate matter during the provision process.

Discussion and Conclusions

Several LCA studies at the international level for forest pulp and paper products show that forest activities contribute very little to almost all environmental impact categories compared with pulp mill operations (Dias et al. 2006, Jawjit et al. 2006, Gonzalez-Garcia et al. 2009). However, in this study, the forest subsystem showed significant contributions to environmental burdens, particularly eutrophication and acidification. Therefore, eucalyptus plantation management methods in China, especially the application of fertilizer, should be an important concern for plantation management in the future.

Dias et al. (2006) concluded in their LCA study for printing and writing paper that transportation plays a vital role in total impacts of acidification and eutrophication. However, in this study, transportation showed very little effect on the environment. This might be due to the differences of research definitions since Dias et al. (2006) included all transportation of raw materials into their analysis, and in our study only the transportation of logs and seedlings were accounted for.

The findings of this study suggested that the pulp mill subsystem is not the major contributor to environmental burdens, and the upstream processes of raw material and energy provision contribute more to the total burdens. This is in agreement with the results of Gonzalez-Garcia et al. (2009) based on a LCA study of total chlorine-free pulp produced in Spain. Therefore, the supply of raw materials and energy shall be an indispensible concern for pulp mills toward sustainable development.

In our study, the environmental impact category of land use changes was not included in the analysis. It was assumed that the establishment of large-scale eucalyptus plantations in China would not lead to land use changes, and there was no natural forest cleared or agricultural crops being displaced as a result of the new eucalyptus plantations. The regulations for plantation establishment projects state that sites for newly established stands are restricted to abandoned lands, degraded lands, barren hills, or nonnatural regenerated stands with existing low-yield plantations (China National Development and Reform Commission 2005).

For LCA studies, precise and accurate data obtained from respective sites are preferred to ensure the data quality (Windsperger et al. 2002, EC-JRC-IES 2010a). In this study, some data from the Eco-invent database, which is based on European conditions, was used in the analysis. These data involved the background processes of five chemicals consumed in the pulp mill and three fertilizers used for plantation management. This may lead to a low level of geographical representative of data quality. However, site-specific data were collected and used in this study whenever possible and feasible, and the Eco-invent data was the most reliable data set for filling data gaps.

Moreover, biogenic CO_2 emission from biomass combustion was assumed to be climate neutral in this study and was excluded in the aggregation of global warming impacts. Recently, Cherubini et al. (2011) stated that all CO_2 emissions from combustion of both fossil fuels and biomass cause a climate impact, and they set up an index of global warming potential (GWP_{bio}) to account for the climate impact of biogenic CO_2 emissions from biomass combustion apart from the sequestrated CO_2 by growing biomass. This issue is probably a new perspective to be included in further studies.

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