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AN ANALYSIS OF THE ENVIRONMENTAL PRESSURE EXERTED BY THE EUCALYPTUS-BASED KRAFT PULP INDUSTRY IN THAILAND

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Abstract. The study reported here focuses on the environmental pressure exerted by large-scale eucalyptus-based kraft pulp industry in Thailand. The objective of this study was to identify the most important sources of greenhouse gases, acidifying and eutrophying compounds and tropospheric ozone precursors, human toxicity compounds and solid waste associated with the kraft pulp industry. To this end, we performed an environmental systems analysis of the kraft pulp industry system in which we distinguished between two subsystems: the eucalyptus forestry subsystem and the kraft pulp production subsystem. The results indicate that the environmental pressure is caused by the kraft pulp production subsystem rather than by the eucalyptus forestry one. The chemical recovery unit was found to be the most important source of carbon dioxide (CO_2) and sulfur dioxide (SO_2) and responsible for more than one-half of the emissions of greenhouse gases and acidifying compounds from eucalyptus-based kraft pulp production in Thailand. Biomass combustion in the energy gene ration unit is an important source of nitrogen oxide (NO_x) and carbon monoxide (CO) which in turn are responsible for over 50% of the emissions of tropospheric ozone precursors. About 73% of the eutrophication is caused by biological aerobic wastewater treatment emitting phosphorus (P). With respect to the eucalyptus forestry, only fertilizer use in eucalyptus plantations is a relevant source of pollution through the emission of nitrous oxide (N_2O) and phosphate (PO_4^{3-}).

Key words: environmental systems analysis, eucalyptus forestry, kraft pulp, Thailand.

Abbreviations: AOX: – Absorbable organic halide; AP: – Acidification potential; CH_4: – Methane; CO: – Carbon monoxide; CO_2: – Carbon dioxide; COD: – Chemical oxygen demand; ECF: – Elemental chlorine free; GWP: – Global warming potentials; LCA: – Life cycle analysis; N_2O: – Nitrous oxide; NO_x: – Nitrogen oxide; NP: – Nutrient potential; POCPs: – Photochemical ozone creation potentials; SIMAPRO: – System for integrated environmental assessment of products; SO_2: – Sulfur dioxide; TRS: – Total reduced sulfur; VOC: – Volatile organic compound.

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1. Introduction

The pulp industry is one of the important fundamental industries in Thailand. With an average annual growth of 5% (DIW, 1999), the production capacity is increasing steadily, and new expansion projects are currently underway. A consequence of this growth is an increasing concern about the environmental impacts. However, to date, there have been no integrated studies that analyze the environmental impact of kraft pulp production in Thailand. One possibility is to carry out an environmental systems analysis. Several environmental systems analysis tools exist that could be useful in this respect and which also help to evaluate the reduction options. One of the analytical tools often used in systems analysis is life cycle analysis (LCA). This approach considers the impacts associated with individual products, taking into account the entire life cycle ranging from raw material acquisition, manufacture, transportation and product use and discard. In Thailand, the majority of the pulp is produced in a eucalyptus-based kraft process (ERIC and TPPIA, 2002). Therefore, a study of the environmental performance of pulp production also needs to take the eucalyptus plantation system into account.

To date, only a few studies on the environmental performance of pulp production in Thailand have been carried out. Ongmongkolkul and Nielsen (2001) included a pulp production component in a study of LCA of paperboard packaging in Thailand. Because of the scarcity of information available on the pulp and paper industry in Thailand, these investigators used the System for Integrated Environmental Assessment of Products (SIMAPRO) as a calculation tool. Their study included a first estimate of the environmental impact of the eucalyptus forestry using data obtained from the Danish wood industry. A recent study by the Thailand Environmental Institute (TEI, 1999) on the industrial environmental index indicated that there were indeed difficulties in obtaining information from the pulp and paper industry for a number of indicators, such as AOX (adsorbable organic halides), TRS (total reduced sulfur) and VOC (volatile organic compounds). Consequently, studies aimed at obtaining more site-specific information are necessary in order to achieve a more accurate and reliable data on the environmental impact of the pulp and paper industry in Thailand. The use of databases from other sources or software, which are not Thailand-based, may not best represent the state of the pulp industry in Thailand. To improve our understanding of the environmental performance of pulp production in Thailand, analyses need to be performed on information obtained locally.

In the study reported here, we focused on the pressure exerted by eucalyptus-based kraft pulp production on the environment in Thailand. When analyzing the emission of pollutants related to the agricultural and industrial sector, one may aim for a full LCA approach of all products. However, with respect to pulp and paper production in Thailand, this is not feasible because of the complexity of the industry. It would be much too time-consuming because of the large number of final products of paper, each having their own unique production process. Therefore, we decided not to perform a full LCA; instead, we focused on eucalyptus kraft pulp as a final product.

Another problem is to determine which parts of the production chain have to be described in order to be able to analyze environmental problems related to eucalyptus plantation and kraft pulp production – without performing a full LCA for all of the products involved. In the other words: what are the system boundaries and how can we decide which inputs, outputs and processes have to be taken into account and which can be omitted? The aim of this study was to contribute to an answer to these questions by analyzing the current environmental pressure exerted by the pulp production in Thailand. This can be done by making an inventory of the sources of greenhouse gases, of acidifying and eutrophying compounds as well as of tropospheric ozone precursors, human toxicity substances and solid wastes from the eucalyptus-based kraft pulp industry in Thailand.

Based on this inventory, our primary aim was to identify the most important sources of the different pollutants. Following the LCA philosophy, we focused not only on pulp production but also on the eucalyptus forestry sector producing the raw material for kraft pulp production. A second aim of our analysis was to reveal which emissions need to be taken into account in a systems analysis aiming at analyzing possible reduction strategies. The analysis reported here was based, as much as possible, on information obtained locally.

2. Methodology

The first step of environmental systems analysis methodology – problem definition – was used in this study. Problem definition includes a clear definition of the system by listing the system inputs, outputs and their relations, and analyzes which inputs, outputs and processes have to be taken into account and which can be omitted (Pluimers, 2001). In this section the system definition is described in detail. The main sources of pollutants, derived from commercial activities in the eucalyptus-based kraft pulp industry, are identified. The method for calculating the emission and environmental impacts are also presented together with the sources of the information.

2.1. System Definition

The definition of system boundaries depends partly on the focus and purpose of the study. In this study the system of the eucalyptus-based kraft pulp industry in Thailand consists of two subsystems – the eucalyptus forestry subsystem and kraft pulp production (Figure 1). The study was restricted to these two subsystems because the purpose of this study was to identify potential contributors to emissions from the eucalyptus forestry and kraft pulp industry which would then be used for determining potential reduction options during subsequent investigations at the level of these two subsystems.

The eucalyptus forestry (only for the purpose of pulp-making) subsystem in Thailand includes four important sources of pollutants: eucalyptus breeding, eucalyptus

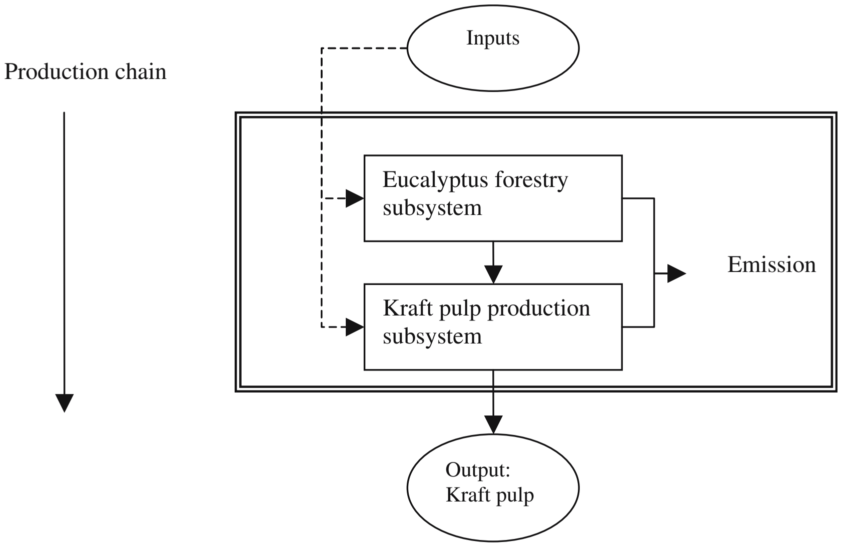

Figure 1. Schematic overview of the kraft pulp industry system in Thailand, including two subsystems: the eucalyptus forestry and the kraft pulp production. The *double line* indicates the system boundary.

plantation, harvesting and transportation. A schematic overview of the eucalyptus forestry subsystem and its environmental impact is shown in Figure 2. Eucalyptus is selected in this study because it supplies the largest proportion (>80%) of raw material for pulp production in Thailand (DIW, 1999) and has progressively taken over the share of other raw materials such as bamboo, bagasses and kenaf. Eucalyptus has such a dominant role because it is fast-growing and its quality can easily be controlled to suit

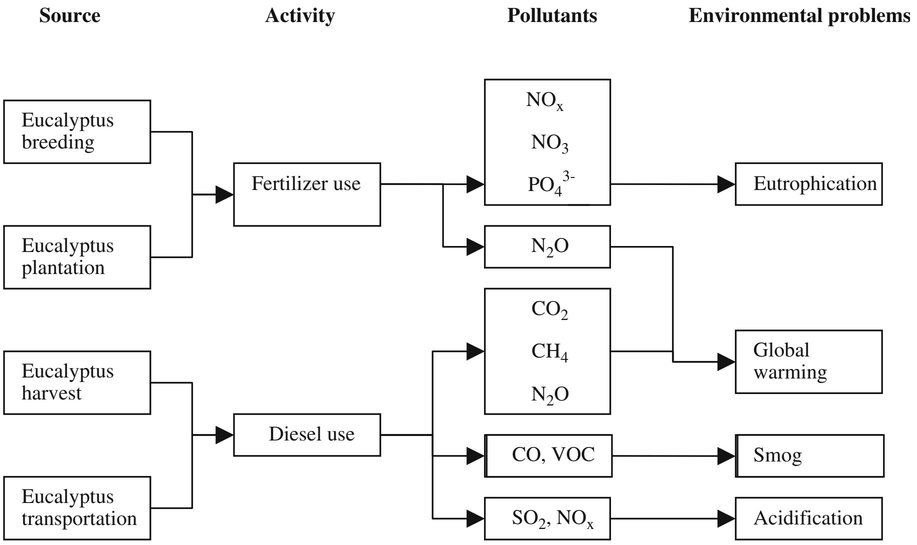

Figure 2. A schematic overview of the eucalyptus forestry subsystem and its environmental impacts.

the pulp production. Although there have been some concerns expressed on the ecological effects of the eucalyptus plantation subsystem, such as soil impoverishment, this aspect was not included in the present study. Time limitation was the main obstacle because a study of ecological effect requires at least 4 years, which is the common number of rotation years for eucalyptus plantations in Thailand. Also, this study focused on the emission of pollutants rather than on natural resource deterioration.

The emissions from four important sources (units) of pollutants are included in the kraft pulp production subsystem in Thailand: the pulp production unit (raw material preparation, pulp digesting, pulp washing, pulp bleaching and sheet forming), chemical recovery unit, energy generation unit and wastewater treatment unit. In kraft pulp mills in Thailand, elemental chlorine free (ECF) is used in pulp bleaching, whereas the biomass (eucalyptus bark as a major source) co-generation system is used for energy (heat and electricity) generation. Activated sludge is favorite wastewater treatment process used in pulp mills in Thailand (TEI, 1997; DIW, 1999; ERIC and TPPIA, 2002). Administrative activities such as electricity use, water use and waste generation from toilets and canteens were not included. A schematic overview of kraft pulp production and its environmental impact is shown in Figure 3. The pulp production process in this study included only the kraft process for three reasons. First, in Thailand the kraft process is more widely applied than other processes using eucalyptus as a raw material; it also has a larger phase (about 80%) in eucalyptus pulp production than other pulp production processes (DIW, 1999). Second, this process is the most versatile process compared with the others and also produces the strongest pulp (UNEP, 1996). Third, good-quality data for the kraft process are readily available.

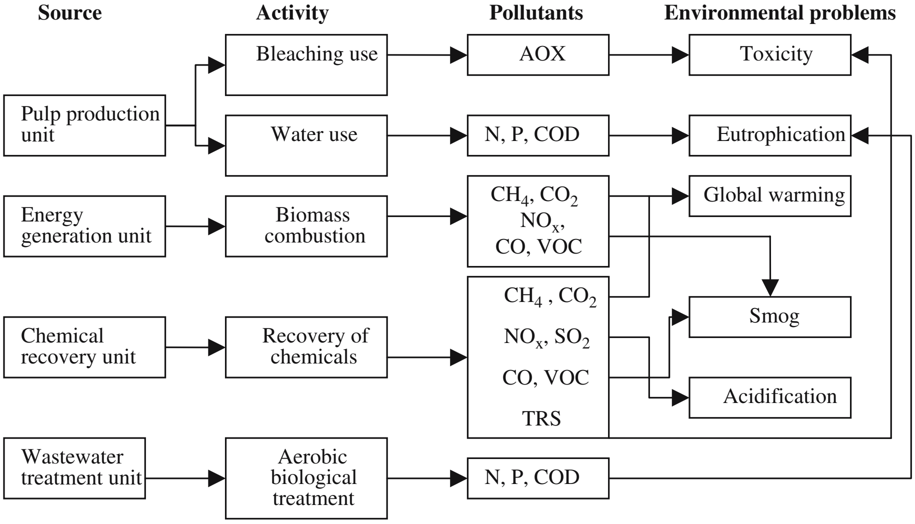

Figure 3. A schematic overview of the kraft pulp production subsystem and its environmental impacts.

2.2. CALCULATION OF EMISSIONS AND ENVIRONMENTAL IMPACTS

In this study we took into account six environmental impacts: global warming, acidification, eutrophication, smog, human toxicity and the production of waste. The emissions related to these impacts include CO_2, CH_4 and N_2O (global warming), SO_2 and NO_x (acidification), COD, PO_4^{3-}, NO_3^-, total N and total P (eutrophication), non-methane (NM)VOCs, CO, CH_4, and NO_x (smog) and particulates, AOX, TRS, SO_2 and NO_x (human toxicity). Only data on the production of waste was directly acquired from mills' reports; other emissions wee calculated as a function of agricultural and industrial activities (shown in Tables I and II) and the emission factors (shown in Table III) using the following equation:

$$\text{EMISSION} = \text{ACTIVITY} \times \text{EMISSION FACTOR} \tag{1}$$

Activities in the eucalyptus forestry subsystem that contribute to the emissions include the use of diesel in harvesting, the transportation of timber to pulp mills and fertilizer use in tree breeding and plantation. The use of diesel in eucalyptus hauling is omitted because man-work is more favorable in Thailand than the use of machinery. Activity data for the calculation of emissions originating from activities associated with the eucalyptus plantation subsystem in Thailand are shown in Table I.

Activities in the kraft pulp production subsystem include biomass combustion, the use of bleaching agents, bunker oil use, lime burning and biological wastewater treatment. When we were unable to quantify the activities which generate pollutants, we calculated the emission using the emission factor related to the production capacity. In this context, the production capacity can be virtually thought of as an activity. In 2001, which we used as our basis for all calculations, 612,000 ton of kraft pulp was produced (ERIC and TPPIA, 2002). Table II shows the activity data for the calculation of emissions from the kraft pulp production subsytem in Thailand. The results of the emission calculations are expressed in tons of pollutants either emitted or generated from the kraft pulp industry system in Thailand per year (ton/year).

The activity data and emission factors that were used to quantify the emissions are considered to be the best data available to date. We first used the activity data and emission factors that were already available on forestry and pulp production in

TABLE I. Activity data for the calculation of emissions from eucalyptus forestry in Thailand (as used in Eq. 1).

Source	Activity	Value	Unit	Reference
Eucalyptus breeding	N-fertilizer use P-fertilizer use	2.46 1.15	ton/year ton/year	Estimated from Cherdkietkul (personal communication)
Eucalyptus plantation	N-fertilizer use P-fertilizer use	1054 1054	ton/year ton/year	All estimated from Poethai (1997) Hoamuangkaew et al. (1999) and Cherdkietkul (personal communication)
Eucalyptus harvest	Diesel use	695, 111	kg fuel/year	All estimated from Poethai (1997) and Schwaiger and Zimmer (1995)
Eucalyptus transportation	Diesel use	2, 040, 000	kg fuel/year	

TABLE II. Activity data for the calculation of emissions from kraft pulp production in Thailand (as used in Eq. 1).

Source	Activity	Value	Unit	Reference
Pulp bleaching unit	Bleaching agent use	6,432	Ton/year	DIW (1999)
Chemical recovery unit	Lime burning	1,970,878	Ton/year	DIW (1999)
Chemical recovery unit	Bunker oil use	916	TJ/year	DIW (1999), estimated from IPCC (1997)
Energy production unit	Biomass combustion	17,258	TJ/year	ERIC and TPPIA (2002)
Wastewater treatment unit	Biological treatment	17,870,400	m^3/year	ERIC and TPPIA (2002)

Thailand. However, some values, such as emission factors in the chemical recovery unit, were not available or well processed. These values, therefore, were obtained from sources which are commonly used and widely accepted, such as emission factors described by the IPCC (1997) and CORINAIR (2000). Moreover, some data could not be obtained directly from a single source, and in these cases we used integrated information from multiple sources to estimate such data (for example, fertilizer use in eucalyptus forestry). Some simplifying assumptions with respect to the calculations also needed to be made. For instance, the average distance between plantation site and pulp production factory was taken to be 100 km, but in reality the distance may vary from 4 to 200 km. In the kraft pulp mill subsystem, biomass-based fuel (eucalyptus bark) was assumed to be the only fuel used for combustion in the boiler because it is by far the major total fuel source (about 90%) (ERIC and TPPIA, 2002), although some dried sludge is also used as additional fuel.

The integrated environmental impact of the emissions wa calculated using classification factor (shown in Table IV) as follows (Heijungs et al., 1992):

$$\text{IMPACT} = \text{EMISSION} \times \text{CLASSIFICATION FACTOR} \tag{2}$$

In th present analysis, classification factors based on six different environmental themes namely global warming, acidification, eutrophication, smog, human toxicity and production of waste, were used.

Global warming

Greenhouse gases, which are the main pollutants contributing to global warming problem, are expressed as GWP (global warming potentials). The GWP is an index of cumulative radiative forcing between the present and some chosen later time horizon caused by a unit mass of gas emitted, expressed relative to the reference gas CO_2 (1 kg CO_2) (Houghton 1994). The combustion of fuels in the pulp mill is the major source of these gases.

In the case of forestry, the growth of eucalyptus acts as a CO_2 sink through photosynthesis. The calculation of CO_2 sequestration, therefore, can be taken into account by following the IPCC (1997) procedure:

TABLE III. Emission factors as used in Eq. 1 for the calculation of the emissions from eucalyptus forestry and kraft pulp production.

Compound emitted	Emission factor	Unit	Reference
Eucalyptus forestry			
Fertilizer use			
N fertilizer use			
N_2O	0.03	kg N_2O-N/kg N	IPCC (1997)
NO_x	0.025	kg NO_x-N/kg N	IPCC (1997)
NO_3^-	0.35	kg NO_3-N/kg N	IPCC (1997)
P fertilizer use			
PO_4^{3-}	0.2	kg PO_4-P/kg P	IPCC (1997)
Diesel use in forestry operation			
Harvest			
CO_2	3150	g/kg fuel	Schwaiger and Zimmer (1995)
N_2O	0.02	g/kg fuel	Schwaiger and Zimmer (1995)
CH_4	6.91	g/kg fuel	Schwaiger and Zimmer (1995)
NO_x	50	g/kg fuel	IPCC (1997)
NMVOC	6.5	g/kg fuel	IPCC (1997)
CO	15	g/kg fuel	IPCC (1997)
Transportation			
CO_2	3180	g/kg fuel	Schwaiger and Zimmer (1995)
N_2O	0.1	g/kg fuel	Schwaiger and Zimmer (1995)
CH_4	0.2	g/kg fuel	Schwaiger and Zimmer (1995)
NO_x	29.8	g/kg fuel	IPCC (1997)
NMVOC	4.7	g/kg fuel	IPCC (1997)
CO	14	g/kg fuel	IPCC (1997)
SO_2	20	g/kg fuel	IPCC (1997), PCD (1996)
Pulp production unit			
Wood handling			
COD	3	kg/ton dried pulp	EC (2001)
Pulp cooking			
TRS	2.5	kg/ton dried pulp	EC (2001)
NMVOC	0.1	kg/ton dried pulp	EC (2001)
Pulp washing			
COD	6	kg/ton dried pulp	EC (2001)
NMVOC	0.27	kg/ton dried pulp	CORINAIR (2000)
Pulp bleaching			
COD	11	kg/ton dried pulp	EC (2001)
N	0.19	kg/ton dried pulp	DIW (1999)
AOX	0.1	kg/kg bleaching use	EPA (1993)
NMVOC	0.05	kg/ton dried pulp	EC (2001)
Energy generation unit			
Fuel combustion (biomass combustion)			
CO_2	110	ton/TJ	IPCC (1997)
CH_4	30	kg/TJ	IPCC (1997)
N_2O	4	kg/TJ	IPCC (1997)
NMVOC	50	kg/TJ	IPCC (1997)
CO	4000	kg/TJ	IPCC (1997)
NO_x	100	kg/TJ	IPCC (1997)
Particulates	1	kg/ton dried pulp	EC (2001)
Chemical recovery unit			
Evaporation tank			
NMVOC	0.05	kg/ton dried pulp	EC (2001)
TRS	0.001	kg/ton dried pulp	Bordado and Gomes (2003)

TABLE III. Continued.

Compound emitted	Emission factor	Unit	Reference
Recovery boiler			
CO_2	6	kg/ton dried pulp	TEI (1997), DIW (1999)
SO_2	0.2	kg/ton dried pulp	Poyry (1992), Bordado and Gomes (2003)
NO_x	1.03	kg/ton dried pulp	Poyry (1992), CORINAIR (2000)
CO	5.5	kg/ton dried pulp	CORINAIR (2000)
NMVOC	0.332	kg/ton dried pulp	CORINAIR (2000)
TRS	0.003	kg/ton dried pulp	Bordado and Gomes (2003)
Particulates	1.2	kg/ton dried pulp	Poyry (1992), Bordado and Gomes (2003)
Smelt tank			
SO_2	0.03	kg/ton dried pulp	Bordado and Gomes (2003)
NO_x	0.01	kg/ton dried pulp	Bordado and Gomes (2003)
TRS	0.009	kg/ton dried pulp	Bordado and Gomes (2003)
Particulates	0.1	kg/ton dried pulp	Bordado and Gomes (2003)
Lime combustion			
CO_2	0.44	ton/ton-lime mud	ERIC and TPPIA (2002)
SO_2	0.55	kg/ton dried pulp	Poyry (1992), Bordado and Gomes (2003)
NO_x	0.33	kg/ton dried pulp	Poyry (1992), Bordado and Gomes (2003)
Particulates	0.1	kg/ton dried pulp	Poyry (1992)
Bunker oil use (in lime kiln)			
CO_2	77.4	ton/TJ	IPCC (1997)
CH_4	2	kg/TJ	IPCC (1997)
N_2O	0.6	kg/TJ	IPCC (1997)
SO_2	1194	kg/TJ	IPCC (1997)
NO_x	200	kg/TJ	IPCC (1997)
CO	10	kg/TJ	IPCC (1997)
NMVOC	5	kg/TJ	IPCC (1997)
Wastewater treatment unit			
CO_2	339.1	g/m^3	CORINAIR (2000)
CH_4	3.7	g/m^3	CORINAIR (2000)
N_2O	0.25	g/m^3	CORINAIR (2000)
P	0.84	kg/ton dried pulp	DIW (1999)

Total annual biomass C uptake by eucalyptus

$$Cs = AP \times GP \times CP \qquad (3)$$

where Cs = annual biomass C uptake (ton C/year); AP = area of plantation (ha); GP = annual biomass growth rate (ton dry matter/ha per year); CP = C fraction in plantation or plant species (ton C/ton dry matter). CO_2 sequestration by eucalyptus (ton/year) is then

$$CO_2 = Cs \times (44/12) \qquad (4)$$

However, although both emissions as well as the CO_2 capture during eucalyptus growth are quantified, the net effect of the two will not be quantified. The net greenhouse gas flux cannot be quantified because CO_2 losses after the produced paper is discarded are not considered. Moreover, this study considered the plantation of eucalyptus as a ‚normal forest’ system. A normal forest consists of an equal

TABLE IV. Classification factors used in Eq. 2 for the emissions of greenhouse gases, acidifying gases, eutrophying compounds, tropospheric ozone precursors and human toxicity compounds.

Environmental theme	Compounds	Classification factor	Reference
Global warming	CO_2	1 kg = 1 CO_2-eq	IPCC (1997)
	CH_4	1 kg = 21 CO_2-eq	
	N_2O	1 kg = 310 CO_2-eq	
Acidification	SO_2	1 kg = 1 SO_2-eq	Heijung et al. (1992)
	NO_x	1 kg = 0.7 1 SO_2-eq	
Eutrophication	NO_x	1 kg = 0.13 PO_4-eq	Heijung et al. (1992)
	NO_3	1 kg = 0.1 PO_4-eq	
	N	1 kg = 0.42 PO_4-eq	
	PO_4	1 kg = 1 PO_4-eq	
	P	1 kg = 3.06 PO_4-eq	
	COD	1 kg = 0.022 PO_4-eq	
Smog	NMVOC	1 kg = 0.416 ethylene-eq	Goedkoop (2000)
	CO	1 kg = 0.027 ethylene-eq	
	CH_4	1 kg = 0.006 ethylene-eq	
	NO_x	1 kg = 0.028 ethylene-eq	
Human toxicity	AOX[a]	1 kg = 1 $C_6H_4Cl_2$-eq	CML (2002)
	TRS[b]	1 kg = 0.22 $C_6H_4Cl_2$-eq	
	SO_2	1 kg = 0.096 $C_6H_4Cl_2$-eq	
	NO_x	1 kg = 1.2 $C_6H_4Cl_2$-eq	
	Particulates	1 kg = 0.82 $C_6H_4Cl_2$-eq	

[a] Classification factor of dichlorobenzene ($C_6H_4Cl_2$) is used for AOX.
[b] Classification factor of hydrogen sulfide (H_2S) is used for TRS.

area of annual age-classes, with the oldest age-class equal to the chosen rotation age. When the oldest age-class is felled, it will be immediately replanted. In a normal forest, the removal of forest products from the oldest stand exactly counterbalances the growth of those products in all other stands. Thus, there is no change in biomass from year to year and therefore no change in carbon. The whole site is therefore a carbon reservoir, but not a net sink or a net source because the annual growth equals the annual losses (Maclaren, 1996). It should be noted that the current methodology of LCA is not able to deal with the evaluation of the sink-effects of carbon in timber products. The CO_2 uptake should, therefore, not be seen as a credit, but as the implementation of the carbon neutrality of wood when its life cycle is taken into consideration (De Feyter, 1995). In the present study, the overall greenhouse gas emission from the eucalyptus-based kraft pulp industry in Thailand is presented and includes CO_2 uptake within the eucalyptus-based pulp only for reasons of comparison (Table V).

Acidification

The kraft pulp production subsystem generates acidifying agents through the production process and chemical recovery since many sulfur-containing chemicals, such as sodium sulfate and sodium sulfide, are used. The combustion of fuel in the pulp mill is the main source of NO_x emissions, although fertilizer use also contributes to the emission of this pollutant. Acidification is measured as the amount of protons released into the terrestrial/aquatic system. The classification factors of acidification

TABLE V. Input data for the calculation of CO_2 sequestration (Eqs. 3 and 4).

Variable	Description	Value	Unit	Reference
AP	Area of plantation	18,133	Ha	Hoamuangkaew et al. (1999)
GP	Annual biomass growth rate	17.4	ton dry matter/ha per year	TEI (1997)
CP	C fraction in plant species	0.5	ton C/ton dry matter	IPCC (1997)

potential (AP) are routinely presented either as moles of H^+ or as kilograms of SO_2 equivalent (Heijungs et al., 1992). The latter was used in this study.

Eutrophication

Fertilizer use in the eucalyptus forestry and pulp production unit (cooking, washing and bleaching) at the kraft pulp mill are the most important activities/sources causing the emission of nitrogen and phosphorus. Enrichment of the water and soil with these nutrients may cause an undesirable shift in the composition of species within the ecosystems, a process called eutrophication. Several models have been proposed to characterize the contribution from life-cycle inventory data to eutrophication. One well-known model has been proposed by Heijungs et al. (1992); this model calculates the nutrification potential (NP) of emissions in relation to the one from the reference compound PO_4^{3-}.

Smog

The combustion of fuel during the pulp production process and transportation of eucalyptus timber causes the emission of VOCs, CO, CH_4 and NO_x, which are considered to be tropospheric ozone precursors. Photochemical ozone creation potentials (POCPs) have been developed to aid in the assessment of the relative contribution of different organic compounds to tropospheric ozone formation. The value of the classification factor of POCPs was taken from Goedkoop (2000) (PReConsultants, Amersfort, the Netherlands) who developed the Eco-indicator 95.

Human toxicity

In the pulp and paper industry, chlorinated compounds are used as the bleaching agents; consequently, one of the more important water pollutants is AOX, which is considered to be a carcinogenic substance generated during the bleaching process. Another toxic substance included in this study is TRS, which is mainly emitted through the chemical recovery unit. This gas causes a bad odor and can harm the human respiratory system. Because classification factors of AOX and TRS are still not available in LCA methodology, we used classification factors of dichlorobenzene ($C_6H_4Cl_2$) for AOX and hydrogen sulfide (H_2S) for TRS. Emissions of particulates, SO_2, NO_x also contribute to human toxicity problem. Classification factors in this environmental theme were taken from CML (2002).

Production of waste

The kraft pulp industry generates both organic and inorganic solid wastes. Most of the organic wastes, such as eucalyptus bark and dried sludge, are sent to the boiler to generate heat and electricity in a co-generation system. These organic wastes are then converted to air pollutants. We focused our study of the production of waste on inorganic wastes, such as lime mud, grit and dregs, which, because they cannot be recycled or reused, are used as landfill. The results of waste production are expressed in terms of amount of solid waste per year (ton/year) because there is no available classification factor.

Although all of the data used in the present study to quantify the emissions and environmental impact was considered to be the best data available, the calculated emissions were subject to uncertainty. We did not carry out a sensitivity or uncertainty analysis to analyze the sensitivity of the calculated emissions, including uncertainties in the assumptions and method used. The classification factors used, such as global warming potentials (GWPs) and acidifying and eutrophying potentials also are subject to uncertainties because these values were not developed in Thailand or on Thailand-based data, although GWPs are commonly used and accepted as classification factor for greenhouse gases (IPCC, 1997). The classification factors we used for calculating the PO_4-equivalents of eutrophying emissions are less widely used and are based on several assumptions (Heijungs et al., 1992). PO_4-equivalents are generally used in LCA studies to indicate the gross effect of eutrophication irrespective of the location of the emissions. However, eutrophication is an environmental problem with typically local effects, and the eutrophication potentials may change when eutrophication is considered as a local problem. Despite these limitations the estimated emission and environmental impact presented here may be the best available at the present time and, therefore, they served the purpose of the study.

3. Results and discussion

3.1. Greenhouse Gases Emission

Approximately 2.9 Mton CO_2-equivalents of greenhouse gas is emitted annually as shown in Table VI. Among the three main components of greenhouse gases – CO_2, CH_4 and N_2O – we found that CO_2 accounts for almost all of the emissions in terms of both actual and equivalent amounts. When we considered the activities that generate greenhouse gases, biomass combustion in the energy production unit ranks the first, with a share of 65%. The second contributor belongs to lime burning, with a relative emission of 30%.

Based on these data, it is clear that if the amount of greenhouse gas emission is considered alone, the focal points of this issue would only be limited to the pulp production process – specifically, biomass combustion and lime burning, as seen in

TABLE VI. Greenhouse gas emissions from eucalyptus forestry and kraft pulp production in Thailand (including emissions from biomass-based CO_2).

Activity/source	CO_2 emission		CH_4 emission		N_2O emission		Total
	Ton/ year	Ton CO_2-eq/ year	Ton/ year	Ton CO_2-eq/ year	Ton/ year	Ton CO_2-eq/ year	Ton CO_2-eq/ year
Eucalyptus plantation	−578,451	−578,451	–	–	–	–	–
Fertilizer use							
Eucalyptus breeding	0	0	0	0	0.1	23	23
Eucalyptus plantation	0	0	0	0	32	9802	9802
Diesel use							
Eucalyptus harvest	2190	2190	5	101	0.01	4	2295
Eucalyptus transportation	6487	6487	0.4	9	0.2	63	6559
Biomass combustion[a]	1,898,424	1,898,424	518	10,873	69	21,400	1,930,697
Chemical recovery unit							
Recovery boiler[a]	3672	3672	0	0	0	0	3672
Lime combustion[a]	867,186	867,186	0	0	0	0	867,186
Bunker oil use	70,924	70,924	2	38	0.5	170	71,133
Wastewater treatment unit	6060	6060	66	1389	4	1385	8833
Total	2,854,943[b]	2,854,943	591	12,409	106	32,848	2,900,309

[a] Sources of biomass-based CO_2.

[b] Total CO_2 emission is not subtracted by CO_2 from sequestration.

Figure 4(I). However, if one analyzes further to the source of emission, it is clear that these two activities become much less significant. The reason for this is that the emissions of CO_2 from biomass combustion can normally be excluded from greenhouse gas inventories since the carbon is derived from trees, in this case, eucalyptus (IPCC, 1997; EPA, 2000). CO_2 emission from lime kiln is also not taken into account in most inventories because of the origin of the carbon contained in the calcium carbonate. In the kraft pulping and chemical recovery process, biomass carbon residing in the non-fibrous portions of wood is dissolved and either emitted as CO_2 from the recovery furnace or captured in sodium carbonate. In the process of converting the sodium carbonate into new pulping chemicals (sodium hydroxide), this biomass carbon (in the form of the carbonate ion) is transferred to calcium carbonate (Miner and Upton, 2002). As a result, when the emission of CO_2 from biomass combustions and lime burning are excluded, the major contributor to greenhouse gases becomes bunker oil use [Figure 4(II)], with the amount of total emission reduced to a mere 0.13 Mton CO_2-eq/year.

Figure 4(II) reveals that although the total contribution from forestry becomes more evident through emissions from fertilizer use and eucalyptus transportation, its proportion is still very minor comparing to that of the kraft pulp production. Upon taking into account further the sequestration of CO_2 by eucalyptus plantations (Eqs. 3 and 4), which is calculated to be approximately 0.6 Mton CO_2-eq/year, this subsystem can be considered to be a minor contributor to the global warming problem. However, the result of CO_2 sequestration by eucalyptus is an underestimation because it is calculated from the sequestration of eucalyptus growth only during the fourth year, which is the year that eucalyptus is normally harvested to

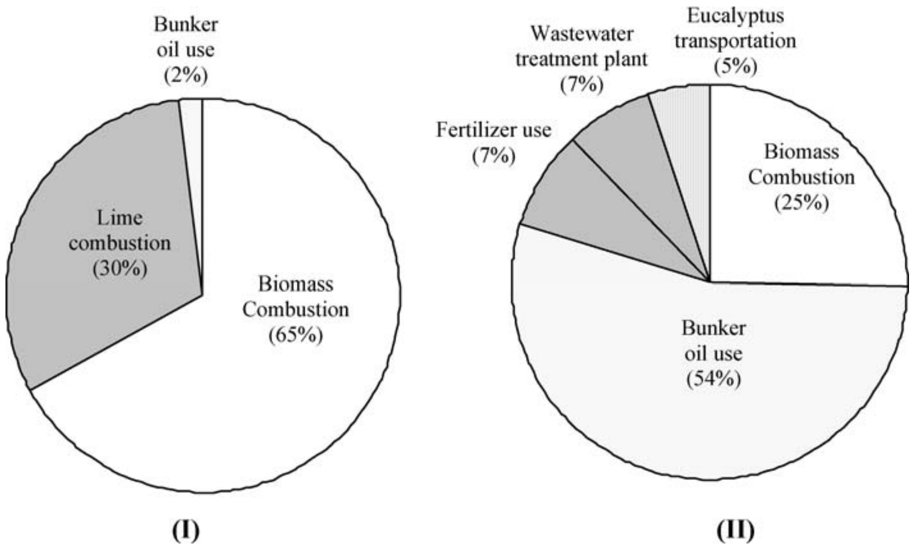

Figure 4. Relative contribution by different activities/sources to total greenhouse gas emissions from eucalyptus forestry and kraft pulp production in Thailand including(**I**) and excluding (**II**) the emission of biomass-based CO_2.

produce the pulp. As a first rough estimate of the total sequestration, one may multiply the calculated 0.6 Mton/year by a factor of four, which will account for the sequestration in the first 3 years of rotation.

3.2. ACIDIFYING GASES EMISSION

The total annual acidifying emissions from SO_2 and NO_x were calculated to be 3.6 kton SO_2-equivalents (Table VII). When we considered the result in terms of actual and SO_2-equivalents, we found that emission of SO_2 is larger than that of NO_x. The chemical recovery unit was found to be the major contributor to SO_2 emission due to the use of Na_2SO_4 in the chemical make-up process and the use of bunker oil in the lime kiln. The emission of NO_x comes mainly from combustion in the biomass boiler and recovery boiler and from bunker oil in the lime kiln.

When the contributor of total acidifying emission was considered, we found that the chemical recovery unit contributes the largest proportion (64% from recovery boiler, smelt tank, lime combustion and bunker oil use) to the total emissions (Figure 5). The next highest contributor comes from biomass combustion resulting in NO_x emissions, with a relative emission of 34%. The eucalyptus forestry subsystem exhibits only a very small contribution (3%) since there is a small NO_x emission from diesel and fertilizer use.

3.3. EUTROPHYING AGENT EMISSION

About 2 kton PO_4-equivalents of eutrophying agents was found to be discharged annually, as shown in Table VIII. Among the six pollutants of eutrophying

TABLE VII. Acidifying emissions from eucalyptus forestry and kraft pulp production in Thailand.

Activity/source	SO_2 emission		NO_x emission		Total	
	Ton/ year	Ton SO_2-eq/ year	Ton/ year	Ton SO_2-eq/ year	Ton SO_2-eq/ year	Percentage
Fertilizer use						
Eucalyptus breeding	0	0	0.06	0.04	0.04	<<1
Eucalyptus plantation	0	0	26	18	18	<1
Diesel use						
Eucalyptus harvest	0	0	35	25	25	1
Eucalyptus transportation	41	41	61	43	84	2
Biomass combustion	0	0	1,726	1,225	1,225	34
Chemical recovery unit						
Recovery boiler	122	122	630	448	570	16
Smelt tank	18	18	6	4	23	1
Lime combustion	337	337	202	143	480	13
Bunker oil use	1,094	1,094	183	130	1,224	34
Total	1,612	1,612	2,870	2,037	3,650	100

agents – NO_3, NO_x, PO_4 from fertilizer use; N and COD from the pulp production unit; P from the wastewater treatment unit – we found that COD was proportionally the most abundant pollutant discharged (12,240 ton/year in total). However, when we considered these eutrophying agents as nutrient potential (NP) substances in terms of PO_4-equivalents, P in the effluent was the most abundant (1,573 ton PO_4-eq/year), followed by COD from the pulp production unit (269 ton PO_4-eq/year) and PO_4 from fertilizer use in eucalyptus plantations (211 ton PO_4-eq/year). The increase in P following biological aerobic treatment derives from the application of fertilizer for stimulating microbial activity. Although the eucalyptus forestry subsystem plays a more significant role in the eutrophication problem than global warming and acidification, the main contributor to this problem is still pollutants (COD and P) from the kraft pulp production subsystem, which accounts for 88% of the total emission (Figure 6).

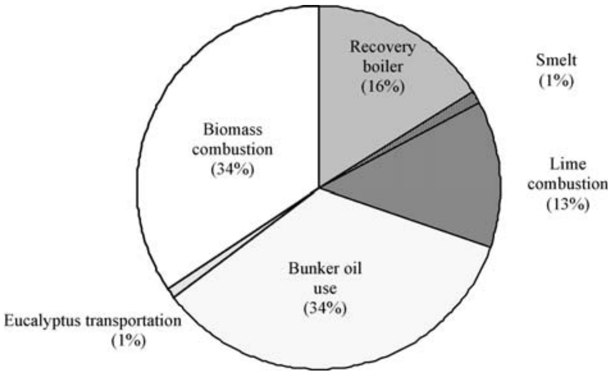

Figure 5. Relative contribution of different activities/sources to total acidifying emissions from eucalyptus forestry and kraft pulp production in Thailand.

TABLE VIII. Eutrophying emissions from eucalyptus forestry and Kraft pulp production in Thailand.

Activity/source	Eutrophying emission		Total (%)
	Ton/year	Ton PO_4-eq/year	
Fertilizer use			
Eucalyptus breeding (NO_x)	0.06	0.01	<<<1
Eucalyptus breeding (NO_3)	0.9	0.1	<< 1
Eucalyptus breeding (PO_4)	0.2	0.2	<< 1
Eucalyptus plantation (NO_x)	26	3	<< 1
Eucalyptus plantation (NO_3)	369	37	2
Eucalyptus plantation (PO_4)	211	211	10
Pulp production unit			
Wood handling (COD)	1,836	40	2
Pulp washing (COD)	3,672	81	4
Pulp bleaching (COD)	6,732	148	7
Pulp bleaching (N)	116	49	2
Wastewater treatment unit			
Phosphorus (P)	514	1,573	73
Total		2,142	100

It should be noted that the amount of fertilizer use in eucalyptus plantations was estimated from the recommendation of the eucalyptus producer company to their contract farmers. In practice, however, the farmers are likely to apply fertilizer at levels lower than those suggested by the producer company. Consequently, the results of nutrient emission from eucalyptus plantations, as presented here, may be overestimated.

3.4. Tropospheric Ozone Precursor Emission

We determined the total emissions of tropospheric ozone precursor compounds to be about 1.7 kton ethylene-eq/year (Table IX). Among the four main components of tropospheric ozone precursors – NMVOC, CO, CH_4 and NO_x – we found that CO accounts for almost all of the emissions in terms of both actual and C_2H_2-equivalent amounts. There are only two main important sources with respect to contributors to the smog problem: biomass combustion and the chemical recovery unit. Biomass combustion in the energy production unit ranks the first, with a share of almost 80%. The second contributor belongs to the chemical recovery unit, with the relative emission share of 14% (Figure 7). Similar to the emission of acidifying gases, the eucalyptus forestry subsystem emits a very small proportion ($<1\%$) of the total tropospheric ozone precursor compounds and can, in fact, be considered to be negligible with respect to this environmental problem.

3.5. Human Toxicity

The total emissions of human toxicity compounds are about 6.9 kton $C_6H_4Cl_2$-eq/year (Table X). Among the four pollutants considered – TRS, AOX, SO_2, NO_x and particulates – we found that AOX emission from pulp bleaching is the highest

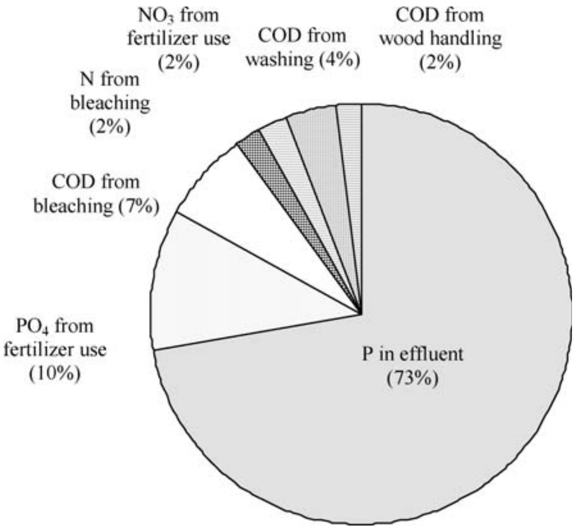

Figure 6. Relative contribution of different activities/sources to total eutrophying emissions from eucalyptus forestry and Kraft pulp production in Thailand.

(1.84 kton/year). Nevertheless, when we considered these compounds as human toxicity substances in terms of $C_6H_4Cl_2$-equivalents, NO_x emissions from biomass combustion exhibit the highest amount (2.07 kton $C_6H_4Cl_2$-eq/year), followed by AOX from pulp bleaching in the pulp production unit and NO_x from the chemical recovery unit. Odorous TRS is emitted as a result of pulp cooking and the chemical recovery unit at amounts of 1530 and 30 ton TRS and 337 and 7 ton $C_6H_4Cl_2$-equivalents, respectively. For the eucalyptus forestry subsystem, emissions of human toxicity compounds were found as a result of diesel use and fertilizer use, but these only account for about 1% of the total emissions (Figure 8).

3.6. THE PRODUCTION OF WASTE

The results of solid waste generation from kraft pulp production were derived directly from mill visits and literature searches. We found that most of the raw material residues (organic residues, bark and wood) are used as fuel in boilers to produce energy. These organic wastes amount to about 283,240 ton/year. Sludge from the wastewater treatment plant, which is also sent to the boilers following a dewatering process, amounts to 9125 ton/year. Solid wastes that cannot be recycled into any of the processing units include solid waste from the recovery unit, such as lime mud, dregs and grits. The final disposal of these wastes is by means of landfill. The amount of lime mud which needs to be landfilled is 60,955 ton/year, whereas amount of dredge, ash, grit and scale that is generated from the energy generation unit, chemical recovery unit and other combustion sources is 93,075 ton/year (DIW, 1999) (Table XI).

TABLE IX. Emissions of tropospheric ozone precursors from eucalyptus forestry and kraft pulp production in Thailand.

Activity/source	NMVOC emission		CO emission		CH_4 emission		NO_x emission		Total	
	Ton/year	tC_2H_2-eq/year	Ton/year	tC_2H_2-eq/year	Ton/year	tC_2H_2-eq/year	Ton/year	tC_2H_2-eq/year	tC_2H_2-eq/year	Percentage
Fertilizer use										
Eucalyptus breeding	0	0	0	0	0	0	0.06	0.002	0.002	<<1
Eucalyptus plantation	0	0	0	0	0	0	26	0.7	1	<<1
Diesel use										
Eucalyptusharvest	5	2	10	0.3	5	0.03	35	1	3	<1
Eucalyptus transportation	10	4	29	1	0	0.002	61	2	6	<1
Pulp production unit										
Pulp cooking	61	25	0	0	0	0	0	0	25	1
Pulp washing	165	69	0	0	0	0	0	0	69	4
Pulp bleaching	31	13	0	0	0	0	0	0	13	1
Biomass combustion	863	359	34,517	932	518	3	1,726	48	1,342	79
Chemical recovery unit										
Evaporation tank	31	13	0	0	0	0	0	0	13	1
Recovery boiler	203	85	3,366	91	0	0	630	18	193	11
Smelt tank	0	0	0	0	0	0	6	0.2	0.2	<<1
Lime combustion	49	20	0	0	0	0	202	6	26	2
Bunker oil use	5	2	9	0.2	2	0.01	183	5	7	<<1
Wastewater treatment unit	0	0	0	0	66	0.4	0	0	0.4	<<1
Total	1,421	591	37,931	1,024	591	4	2,870	80	1,699	100

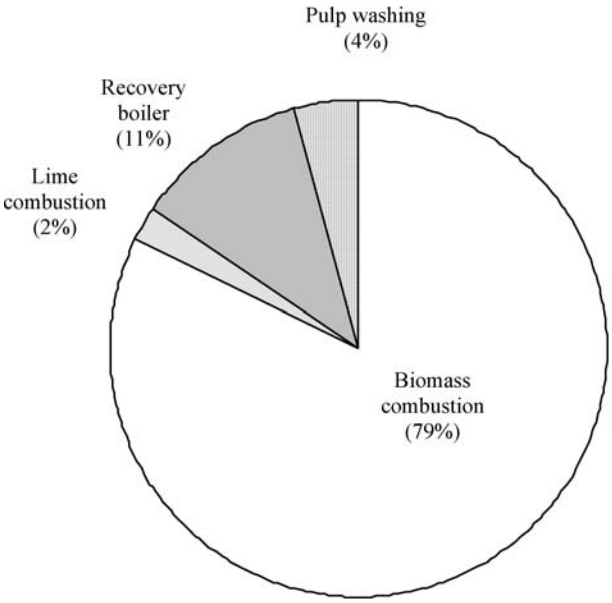

Figure 7. Relative contribution (ethylene equivalent) of different activities/sources to the total emission of tropospheric ozone precursors from kraft pulp production in Thailand.

4. Conclusion

The sources of environmental pressure intrinsic in the kraft pulp industry in Thailand have been identified for six environmental problems: global warming, acidification, eutrophication, smog, human toxicity and the production of waste. To this end, we distinguished between two subsystems within the kraft pulp industry: eucalyptus forestry and kraft pulp production. We found that emissions from the eucalyptus forestry subsystem are small compared to those from the kraft pulp production. The environmental pressure from forestry can thus be considered to be a minor contributor to all environmental problems falling within the framework of the kraft pulp industry in Thailand.

With respect to the kraft pulp production subsystem, we found that there are four important sources of environmental pressure, namely, the energy generation unit, chemical recovery units, pulp production units and wastewater treatment unit. The combustion of fuels, both biomass and bunker oil, is the most important source of pollution related to greenhouse gases, smog precursors and human toxicity compounds, with CO_2, CO and NO_x being the most important pollutants, respectively. The chemical recovery unit is the main source of SO_2 and inorganic solid waste related to the problem of acidification and the production of waste, respectively. Bleaching in the pulp production unit is the major source of AOX causing toxicity problems, whereas the aerobic wastewater treatment unit is the most important cause of eutrophication, with the emission of P as the prime cause. For odor

TABLE X. Emissions of human toxicity compounds from eucalyptus forestry and Kraft pulp production in Thailand.

Activity/source	SO_2 emission		NO_x emission		Particulates emission		TRS emission		AOX emission		Total	
	t/year	tDCB[a]-eq/year	Ton/year	tDCB-eq/year	t/year	tDCB-eq/year	Ton/year	tDCB-eq/year	Ton/year	tDCB-eq/year	tDCB-eq/year	Percentage
Fertilizer use												
Eucalyptus breeding	0	0	0.06	0.1	0	0	0	0	0	0	0.1	<<1
Eucalyptus plantation	0	0	26	31	0	0	0	0	0	0	32	<1
Diesel use												
Eucalyptus harvest	0	0	35	42	0	0	0	0	0	0	42	<1
Eucalyptus transportation	41	4	61	73	0	0	0	0	0	0	77	1
Pulp production unit												
Pulp cooking	0	0	0	0	0	0	1,530	337	0	0	337	5
Pulp bleaching	0	0	0	0	0	0	0	0	1,843	1,843	1,843	26
Biomass combustion	0	0	1,726	2,071	612	502	0	0	0	0	2,573	37
Chemical recovery unit												
Recovery boiler	122	12	630	756	734	602	2	0.4	0	0	1,371	20
Smelt tank	18	2	6	7	61	50	6	1	0	0	61	<1
Lime combustion	337	32	202	242	61	50	28	6	0	0	331	5
Bunker oil use	1,094	105	183	220	0	0	0	0	0	0	325	5
Total	1,612	155	2,870	3,443	1,469	1,204	1,565	344	1,843	1,843	6,990	100

[a] DCB, Dichlorobenzene ($C_6H_4Cl_2$).

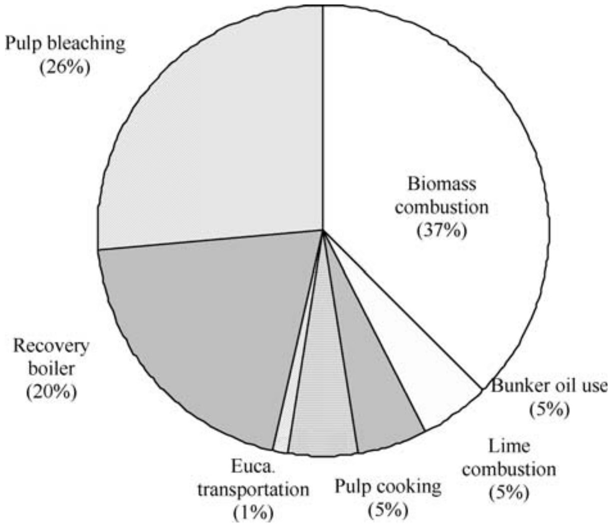

Figure 8. Relative contribution (ethylene equivalent) of different activities/sources to total emission of human toxicity compounds from kraft pulp production in Thailand.

TABLE XI. Solid waste generation from kraft pulp production in Thailand.

Pollutant	Activity	Source	Emission (ton/year)
Organic waste			
Raw materials residue	Debarking	Raw material preparation	283,240
Sludge	Wastewater treatment	Wastewater treatment plant	9,125
Inorganic waste			
Lime mud residue	Chemical recovery	Chemical recovery unit	60,955
Dregs, grit and ashes	Fuel combustion	Chemical recovery unit and energy generation unit	93,075

problems, pulp cooking and the chemical recovery unit were found to be the important sources of TRS emission.

In additions to the major emissions mentioned above, other emissions, which contribute to at least 85% of the total emissions in each environmental theme, should also be taken into account when identifying options to reduce the environmental impact of the kraft pulp industry in Thailand (Table XII). In conclusion, the sources of emissions which we have taken into account are: (1) the energy generation unit through biomass combustion with emissions of CH_4, N_2O, NO_x, CO, VOC and particulates; (2) bunker oil use in lime burning with emissions of CO_2 and SO_2; (3) lime combustion with emissions of SO_2, NO_x, VOC; (4) the pulp production unit with emissions of AOX, COD and TRS; (5) the wastewater treatment unit with emissions of P; (6) eucalyptus plantation through fertilizer use with emissions of N_2O and PO_4^{3-}.

TABLE XII. The emission of pollutants that are responsible for 85% or more of the total contribution to global warming, acidification, eutrophication, smog and human toxicity.

Environmental theme	Pollutant	Source	Contribution total emission (%)
Global warming	CO_2	Biomass combustion	65
(including biomass-based CO_2)	CO_2	Lime combustion	30
Global warming	CO_2	Bunker oil use[a]	54
(excluding biomass-based CO_2)	N_2O	Biomass combustion	16
	CH_4	Biomass combustion	8
	N_2O	Fertilizer use in eucalyptus plantation	7
Acidification	NO_x	Biomass combustion	34
	SO_2	Bunker oil use	30
	NO_x	Recovery boiler	12
	SO_2	Lime combustion	9
	NO_x	Lime combustion	4
Eutrophication	P	Wastewater treatment unit	73
	PO_4^{3-}	Fertilizer use in eucalyptus plantation	10
	COD	Wastewater treatment unit	7
Smog	CO	Biomass combustion	55
	NMVOC	Biomass combustion	21
	CO	Recovery boiler	5
	NMVOC	Recovery boiler	5
Human toxicity	NO_x	Biomass combustion	30
	AOX	Pulp bleaching	26
	NO_x	Recovery boiler	11
	Particulate	Recovery boiler	9
	Particulate	Biomass combustion	7
	TRS	Pulp cooking	5

[a] Bunker oil is used in lime kiln.

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