รายงานการวิจัย

ปริมาณก๊าซเรือนกระจกจากอุตสาหกรรมยางและการใช้เทคโนโลยีสะอาดเพื่อการควบคุม

Greenhouse Gases Emissions of Rubber Industries and Theirs Control by Application of Clean Technologies

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คณะวิทยาศาสตร์และเทคโนโลยี
มหาวิทยาลัยเทคโนโลยีราชมงคลศรีวิชัย

ได้รับการสนับสนุนทุนวิจัยจากมหาวิทยาลัยเทคโนโลยีราชมงคลศรีวิชัย
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กิตติกรรมประกาศ

คณะผู้วิจัยขอขอบคุณสำนักงานคณะกรรมการการวิจัยแห่งชาติ (วช.) และ มหาวิทยาลัยเทคโนโลยีราชมงคลศรีวิชัยที่ได้สนับสนุนทุนการทำวิจัยในครั้งนี้ และคณะผู้วิจัยขอขอบคุณ WIMWK (Wageningen Institute of Environment and Climate Research) ที่ได้ให้ทุนหัวหน้าโครงการไปทำวิจัยเพิ่มเติมในเรื่องแบบจำลองการคำนวณการปลดปล่อยก๊าซเรือนกระจกที่ประเทศเนเธอร์แลนด์

คณะผู้วิจัยขอขอบคุณเกษตรกรชาวสวนยางพารา, เจ้าของสถานประกอบการ และโรงงานแปรรูปผลิตภัณฑ์ยางทุกแห่งที่ได้ให้ความร่วมมือในการให้ข้อมูลประกอบการวิจัยเป็นอย่างดียิ่ง ซึ่งทำให้งานวิจัยมีความน่าเชื่อถือและถูกต้องมากยิ่งขึ้น และขอขอบคุณ นายทัดพงศ์ แวววศักดิ์, นางสาวปาจรีย์ เอียดแก้ว และนางสาวเบญจวรรณ แก้วคง ที่ได้ช่วยเหลือในการเก็บข้อมูลในการวิจัยครั้งนี้เป็นอย่างดี

คณะผู้วิจัยขอขอบคุณคณะวิทยาศาสตร์และเทคโนโลยี ที่เปิดโอกาสให้ได้ทำการวิจัยเพื่อเสริมสร้างศักยภาพทางวิชาการ และขอขอบคุณ Journal of Cleaner Production ที่ได้ตอบรับการตีพิมพ์งานวิจัยชิ้นนี้ใน Volume 18, Issue 5, March 2010, Pages 403-411 สุดท้ายคณะผู้วิจัยขอขอบคุณครอบครัว สำหรับความเข้าใจและกำลังใจที่มีให้ตลอดมา

ปริมาณก๊าซเรือนกระจกจากอุตสาหกรรมยางและการใช้เทคโนโลยีสะอาดเพื่อการควบคุม

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บทคัดย่อ

งานวิจัยชิ้นนี้มีจุดประสงค์เพื่อคำนวณปริมาณการปลดปล่อยก๊าซเรือนกระจกจากการผลิตผลิตภัณฑ์ยางขั้นต้นได้แก่ น้ำยางสด, น้ำยางข้น, ยางแท่ง STR 20 และยางแผ่นรมควัน โดยขอบเขตการศึกษาครอบคลุมทั้งกิจกรรมในภาคการเกษตรซึ่งได้แก่ การปลูกและการดูแลยางพารา, การขนส่งน้ำยางสด และกิจกรรมในภาคอุตสาหกรรมคือการผลิตผลิตภัณฑ์ในโรงงาน ซึ่งผลการศึกษาพบว่าหากมีการปลูกยางพาราซ้ำในพื้นที่ปลูกเดิม ปริมาณการปล่อยก๊าซเรือนกระจกต่อการผลิต น้ำยางข้น, ยางแท่ง STR 20 และยางแผ่นรมควัน มีค่าเท่ากับ 0.54, 0.70 และ 0.64 ตัน CO_2 เทียบเท่า/ 1 ตันของผลิตภัณฑ์ตามลำดับ อย่างไรก็ตามหากการปลูกยางพาราในพื้นที่ที่เป็นป่าธรรมชาติ ปริมาณการปล่อยก๊าซเรือนกระจกจะเพิ่มสูงขึ้นอย่างมากเป็น 13, 13 และ 21 ตัน CO_2 เทียบเท่า/ 1 ตันของผลิตภัณฑ์ตามลำดับ ซึ่งผลการคำนวณที่ได้นี้สามารถใช้เป็นฐานข้อมูลในการคำนวณการปลดปล่อยก๊าซเรือนกระจกสำหรับผลิตภัณฑ์ปลายทางต่อไป ในรายงานฉบับนี้ยังได้นำเสนอการใช้ทางเลือกเทคโนโลยีสะอาดเพื่อลดการปลดปล่อยก๊าซเรือนกระจกจากอุตสาหกรรมยางขั้นต้นด้วย

คำสำคัญ: ก๊าซเรือนกระจก, ยางพารา, น้ำยางข้น, ยางแท่ง, ยางแผ่นรมควัน

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Greenhouse Gases Emissions of Rubber Industries and Theirs Control by Application of Clean Technologies

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Abstract

Thailand is currently the world's largest natural rubber producer. In this study emissions of greenhouse gases associated with the production of fresh latex, and three primary rubber products, including concentrated latex, block rubber (STR 20), and ribbed smoked sheet (RSS) in Thailand, were presented. Both industrial activities in the rubber mills and the agricultural activities in rubber tree plantation are taken into account. For the case that rubber plantations have been located on cultivated lands for more than 60 years, the overall emissions from the production of concentrated latex, STR 20, and RSS amount to 0.54, 0.70, and 0.64 ton CO_2-eq/ ton product, respectively. Such emissions are largely associated with energy use and the use of synthetic fertilizers. For the case that tropical forests have been converted to rubber plantations, the emissions are much higher because of carbon loss from land conversion: 13, 13, and 21 ton CO_2-eq/ ton product for concentrated latex, STR 20, and RSS, respectively. Discussions on the implications of the results for strategies to reduce greenhouse gas emissions from rubber production are also presented.

Keywords: Greenhouse gases, Rubber, Latex, Concentrated latex, Block rubber, Ribbed smoked sheet

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Greenhouse Gases Emissions of Rubber Industries and Theirs Control by Application of Clean Technologies

Warit Jawjit Carolien Kroeze Suwat Rattanapan

1. INTRODUCTION

Thailand is an important rubber producing country. About 35% of the latex produced worldwide is from Thailand (OAE, 2007). Para rubber (*Hevea brasiliensis)* was introduced to Thailand around the year 1910. Since then, rubber plantations and rubber-related industries have been expanding rapidly. Rubber industry in Thailand is of economic and social importance because of its production value, the revenues from export and the employment in this sector. About six million people are involved in rubber plantation (TRA, 2009), whereas about 0.6 million people work in rubber industries (MOL, 2008). Since 2003, Thailand has become the world's largest natural rubber (NR) producer (RRI, 2008). In 2008, the fresh latex production in Thailand was about 3 million ton with an average yield of 5.64 ton fresh latex per hectare (OAE, 2007). The worldwide demand for natural rubber product is growing, especially in China and India, and this will lead to additional rubber plantations and productions. Most rubber plantation sites (70%) are at the south of Thailand (MOL, 2008). Since the rubber plantation area in the south becomes limited, new plantations have been developed in eastern and northeastern Thailand in the past decade (Hammecker et al., 2006).

The economic lifetime of rubber plantations in Thailand is around 20-25 years. During the first seven years the trees grow without possibilities to tap latex. This period is followed by 13-18 productive years (Allen, 2004). Fresh latex is extracted by tapping from the rubber trees. The fresh latex is collected as a liquid. The fresh latex can then be processed to primary rubber products, which are subsequently processed to different final rubber products (Fig. 1). The most important primary (intermediate) rubber products include *concentrated latex* (raw material for dipped products such as medical gloves and condoms), *block rubber* (raw material for high viscosity products such as soles and belts), and *ribbed smoked sheet rubber* (raw material for vehicle tires and industrial rubber parts) (Korwuttikulrungsee, 2002).

Since natural rubber products are being exported to the international market, it has been challenging for Thai rubber entrepreneurs to seek for appropriate environmental measures to produce environmentally friendly rubber products. Traditionally, environmental management in rubber mills focused on pollution reduction, especially through wastewater treatment and air pollution control (Rakkoed et al., 1999; Nguyen, 1999). Thailand has signed the Kyoto protocol in 1998, and is currently implementing a strategic climate plan for the period 2008 – 2012. This plan consists of six important strategies, including building capacity to adapt to climate impact, promoting greenhouse gas mitigation, and creating awareness (Thammakul, 2009). According to Thailand's initial national communication (ONEP, 2000), Total Thai greenhouse gas emissions were 286 Tg CO2-equivalents in the mid-nineties, of which about 75 Tg are from land use change and forestry, about 60 Tg from agriculture, and about 15 from industry. Global warming has been gaining attention from the industrial sector during the last decade. As a result, several studies were carried out to identify measures to reduce fuel use and energy consumption in the production of rubber products (DIW, 2001; PCD, 2005; STO, 2005). The Thai Rubber Association has recently been considering the opportunity to apply for a Clean Development Mechanism (CDM) project under the Kyoto Protocol, and also the possibility to start a “Carbon Label” for rubber products (TRA, 2008). This, however, requires information on greenhouse gas emissions from the rubber industry. However, such information is, to our knowledge, not available.

The objective of this study is, therefore, to quantify emissions of greenhouse gas emissions associated with the production of fresh latex and primary rubber products in Thailand, and to discuss options to reduce these emissions.

2. GOAL AND SCOPE DEFINITION

2.1 Goal definition

Emissions of greenhouse gas emissions associated with the production of fresh latex, and three primary rubber products (including concentrated latex, block rubber, and ribbed smoked sheet) produced in Thailand were quantified. Besides industrial activities in the rubber mills, the agricultural activities in rubber tree plantations are taken into account. Potential options for reducing greenhouse gas emissions from rubber production are discussed.

2.2 System boundary

The rubber products considered in this study include fresh latex, concentrated latex, block rubber, and ribbed smoke sheet. *Fresh latex* refers to latex that is collected from rubber trees by farmers, and then transported to rubber processing mills. Ammonia may be added to the latex to prevent coagulation before reaching the mill (Nambiar et al., 1981). *Concentrated latex* refers to the latex which is processed by centrifuging, and has a Dry Rubber Content (DRC) of at least 60%. *Block rubber* in this study refers to *STR 20* block rubber (STR = Standard Thai Rubber). STR 20 has the largest share (80%) in all block rubber. It is produced from dried rubber in the form of cup lumps, tree laces, bark scrap and earth scrap (Leong et al., 2003). Blackened STR 20 is usually used as raw material for vehicle tires, belts and rubber parts in for industry. STR 20 will be refered as block rubber in the rest of this paper. *Ribbed smoked sheet (RSS)* refers to rubber sheets that are transformed from liquid fresh latex to solid rubber sheets by adding formic acid, and consecutive smoke drying at 50-60 ^{o}C in order to preserve the quality of the rubber (Tekasakul and Promtong, 2008). Smoked sheets are categorized to different grades (RSS1- RSS5) based on their quality, color and contaminations.

Two main systems in our study were distinguished, including *rubber plantations* (i.e. the production of fresh latex), and *rubber mills* (i.e. the production of concentrated latex, block STR 20, and RSS). As shown in Fig. 2, each system includes the production of raw materials which are used in agricultural and industrial activities, and the activities associated with the production of fresh latex and the three primary rubber products. The activities in the *rubber plantations* include the production of N and P fertilizer, the production of diesel (used in tillage and fresh latex transportation), land conversion, N fertilizer use, diesel use in tillage, and diesel use in fresh latex transportation. Activities in the *rubber mills* include the production of electricity, the production of diesel, the production of LPG (Liquefied Petroleum Gas), the production of ammonia, diesel use, LPG use, and wood use. Chemical use in the production of concentrated latex is dominated by ammonia. In the production of STR 20, and RSS chemical use is rare, and can be considered negligible. Transport of N and P fertilizers, ammonia, diesel and LPG is not considered. Wastewater treatment may be a source of greenhouse gases, in particular when anaerobic treatment is applied (which could result in CH_4 emissions). Most wastewater treatment at rubber mills in Thailand are, however, aerobic systems (mainly oxidation ponds). We, therefore, assume that the associated greenhouse gas emissions are minor, and excluded these from the study.

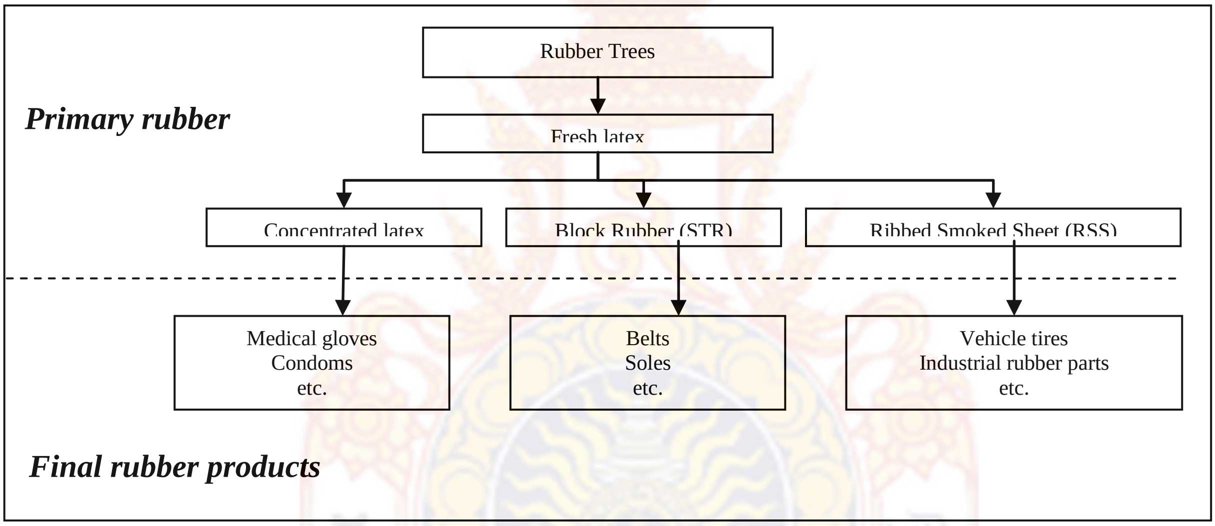


Figure 1 Schematic diagram of production of primary rubber product

2.3 Functional unit

Emissions of the greenhouse gases CO_2, CH_4 and N_2O were calculated. The emissions associated with rubber products are first calculated in term of kg CO_2 (CH_4, N_2O) per ton of rubber product (fresh latex, concentrated latex, STR 20, RSS), and then converted to CO_2-equivalents using Global Warming Potentials (GWP). The GWPs are 21 and 310 for CH_4 and N_2O, respectively (IPCC, 2006).

3. METHODOLOGY

3.1 Calculation of Greenhouse Gas Emissions

Most emissions of greenhouse gases associated with the production of fresh latex, and primary rubber products are quantified as a function of activities (shown in Table 1) and emission factors (shown in Table 2), using the following equation:

$$E_{x,\,i,\,j} \;\; = SUM_{\,i,\,j}\ (A_{\,i,\,j}\ x\ \ EF_{x,\,i\,,j}\ x\ GWP_{x}) \quad 1)$$

where $E_{x,\,i,\,j}$ are emissions of greenhouse gas *x* (index for type of greenhouse gases: CO_2, CH_4, N_2O) associated with activities *i* (index for type of activities as shown in Table 1) in the production of product *j* (index for type of products: fresh latex, concentrated latex, STR, RSS) (kg CO_2-eq/ ton product). $A_{\,i,j}$ is the level of activity *i* in the production of product *j* , and $EF_{x,\,i\,\,,j}$ is the emission factor for greenhouse gas *x* due to activity *i* in production of product *j* . GWP_x is the global warming potential of greenhouse gas *x* as described in section 2. The emissions are calculated as annual total emissions per ton or rubber product in Thailand for the year 2008.

Greenhouse gas emissions were estimated largely following the IPCC 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), unless local information provides better estimates. Most activity data that we use are from local sources, as discussed below. We consider this approach to be the most appropriate for our purpose. Good quality local information is preferred, but when not available, the IPCC Guidelines provide an internationally accepted alternative. Emission factors are largely from IPCC (IPCC, 2006). Most emission factors for CO_2 and CH_4 are readily available from the IPCC Guidelines. For N_2O emissions some additional assumptions needed to be made. For the industrial production of synthetic fertilizers, we assume that there is no abatement of N_2O emissions. The fertilizers used in Thailand are mainly produced by a mix of technologies. Following the IPCC Guidelines, we use an emission factor of 7 kg N_2O/ton nitric acid (0.022 kg N_2O/ kg synthetic fertilizer-N produced), which is within the range for existing technologies (5-9 kg N_2O/ton nitric acid).

N_2O can also be emitted from soils, because of bacterial processes such as nitrification and denitrification that are part of the natural nitrogen cycle (Mosier et al., 1998). Rubber production may increase these natural emissions in several ways. First, there are so-called direct emissions, caused by fertilization or enhanced N mineralization as a result of land use. Second, there are indirect emissions. These are emissions of N_2O that are induced by fertilizer use, but taking place elsewhere after nitrogen losses from the fertilized fields. These losses include N leaching and runoff, and emissions of fertilizer N as nitrogen oxides (NO_x) or ammonia (NH_3). In this study, we assume that there is no animal manure used in rubber industry, and that the emissions as a result of crop residues are negligible. For all soil emissions, we use emission factors from IPCC (IPCC, 2006) (Table 2). We furthermore assume that rubber is produced on mineral soils.

Conversion of natural forests to agriculture in the humid tropics leads to a reduction in ecosystem carbon storage due to the immediate removal of aboveground biomass and a gradual subsequent reduction in soil organic carbon [17]. Rubber plantations in Thailand are located on lands that have been converted natural forest, crop cultivation sites, rice paddy fields, and other types of land use. In general, the type of land conversion largely affects the overall greenhouse gas emissions from cultivated soils (Murdiyarso et al., 2002). The current area of rubber plantation in Thailand is 2.46 million ha. Most of rubber plantation sites (70%) are in the south of Thailand, and have been planted with rubber trees for 60- 80 years. Other regions have been developed for rubber plantations during the last two decades. To quantify emissions from land conversion, we distinguish between two cases: one is typical for the south and the other for eastern and southern regions of Thailand. We assume that there is no change in carbon stock in rubber plantation sites in the south (1.78 million ha). This is following the IPCC Good Practice Guidelines for Greenhouse Gas Inventories, indicating that after 20 years carbon stocks approach to a new equilibrium (IPCC, 2004). We realize that the actual length of this transition period is country-specific, and depends on natural and ecological circumstances. However, for Thailand no detailed information exists to specify this period in more detail (ONEP, 2000). Therefore, using the IPCC default of 20 years seems appropriate. For other regions Thailand (i.e. not in the south), we assume that rubber plantations (0.68 million ha) are on lands that have been converted from tropical forest. In this case, large changes in biomass carbon stocks occur during the land conversion, since primary forests store more carbon than rubber plantations (Reijnders and Huijbregt, 2006; Gnanavelrajah et al., 2008).

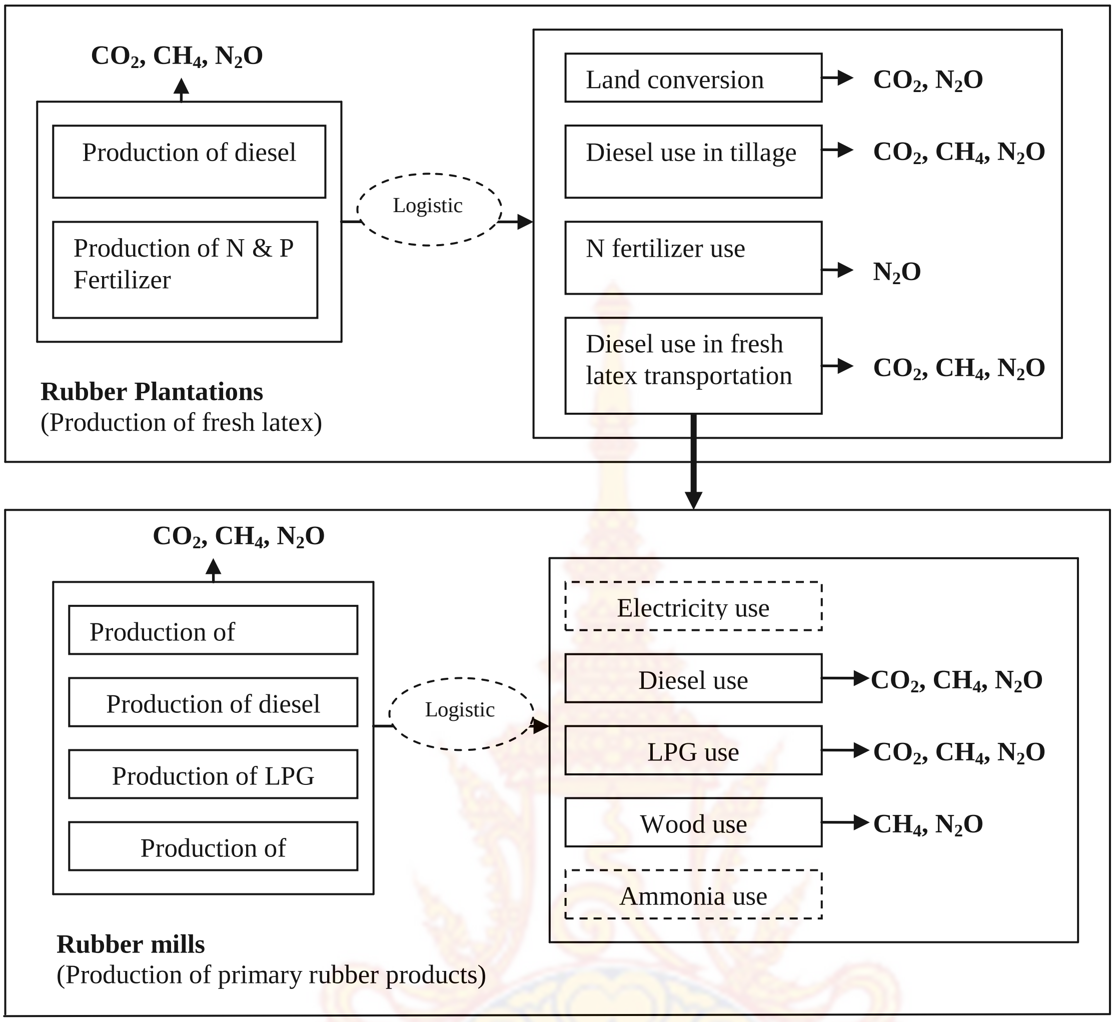


Figure 2 Schematic overview of the production of fresh latex and primary rubber products (concentrated latex, STR 20 and RSS) and associated emissions of greenhouse gases. Solid lines indicated that the activities or processes are considered in this study, while dotted lines indicate that the activities or processes are not considered.

3.2 Activity Data

The activity data used in this study are both from primary and secondary sources (Table 1). Rubber plantation sites were visited several times to interview 33 Thai farmers about their practices on, for instance, land preparation for planting rubber trees, diesel use in tillage, fertilizer use, number of tapping days in a year, distance over which fresh latex is transported to rubber mills. In addition, questionnaires were sent to 8 Thai rubber mills (3 concentrated latex mills, 3 STR mills, 2 RSS mills) including questions on the production capacity, production process, electricity and fuel use, chemicals use, and pollution abatement practices. Four rubber mills were visited (2 concentrated latex mills, 1 STR mill, and 1 RSS mill) to obtain more detailed information on energy and environmental issues from local technicians.

Secondary data is used for completion, comparison and validation. Activities data on rubber plantation practices and fertilizer use were taken from the Thailand Rubber Research Institute (RRI, 2009) and Korwuttikulrungsee (2002). Electricity use, fuel consumption, and chemical use in rubber processing mills were taken from studies performed by the Department of Industrial Work (DIW, 2001), the Pollution Control Department (PCD, 2005), and the Safety Technology Office (STO, 2005). The results from our surveys and questionnaires are generally in line with the literature. All activity data used in this study are presented in Table 1.

Table 1 Activity data ($A_{i,j}$) used for the calculation of greenhouse gas emissions from the production of fresh latex, and primary rubber products (as used in equation 1)

Activity data	**value**	**Unit [1)]**	**Source [2)]**
Diesel use in tillage	0.78	liter/ha/year	Farmer interviews and field visits
N Fertilizer use	70	kg-N/ha/year	Farmer interviews and RRI (2009)
P fertilizer use	35	kg-P/ha/year	
Diesel use for fresh latex transportation	5	Liter/trip [3)]	Farmer interviews
Ammonia use in concentrated latex mills	17	kg/ton conc. latex	Questionnaires, technicians interviews, mill visits; DIW (2001); PCD (2005); STO (2005)
Electricity use			
- in concentrated latex mills	100	kWh/ton conc. latex	
- in block rubber (STR) mills	220	kWh/ton STR	
- in ribbed smoked sheet (RSS) mills	10	kWh/ton RSS	
Diesel use			
- in concentrated latex mills	300	MJ/ton conc. latex	
- in block rubber (STR) mills	1000	MJ/ton STR	
- in ribbed smoked sheet (RSS) mills	150	MJ/ton RSS	
LPG use in block rubber (STR) mills	1252	MJ/ton STR	
Wood use in ribbed smoked sheet (RSS) mills	900	MJ/ton RSS	

1) The emissions per hectare are converted to ton CO_2-equivalents/ton of fresh latex, assuming a yield of 5.64 ton fresh latex per hectare/year
2) See text for details on interviews and site visits
3) The average distance from rubber plantation sites to rubber mills is about 30 km (round trip 60 km)

Table 2 Emission factors [1)] ($EF_{x, i, j}$) used for calculation of greenhouse gases emissions from production of fresh latex, and primary rubber products (as used in equation (1))

Activity	Gas	Emission factor	Unit
Diesel use in tractors for tillage	CO_2	73	g/MJ
	CH_4	0.004	g/MJ
	N_2O	0.03	g/MJ
Production of N- Fertilizer: energy related [a)]	CO_2	2.5	kg/kg N
	CH_4	2.70E-05	kg/kg N
	N_2O	3.80E-05	kg/kg N
Production of N- Fertilizer: process related	N_2O	0.022	kg/kg N
N_2O direct emissions from fertilizer use	N_2O	0.01	kg N_2O-N/kg N
N_2O direct emission from cultivation of mineral forest soil	N_2O	0.01	kg N_2O-N/kg N mineralized from mineral soil
N_2O indirect emission after N leaching and runoff	N_2O	0.00225	kg N_2O-N/ kg N use
N_2O indirect emission after emission of fertilizer N as NO_x and NH_3	N_2O	0.001	kg N_2O-N/ kg N use
Production of P-fertilizer: energy related [a)]	CO_2	0.705	kg/kg P
	CH_4	7.60E-06	kg/kg P
	N_2O	1.06E-06	kg/kg P
Production of ammonia	CO_2	3.3	ton/ ton NH_3
Production of Electricity[b)]	CO_2	0.624	ton/MWh
	CH_4	0.02	kg/MWh
	N_2O	0.005	kg/MWh
Diesel use in latex transportation by pick-up cars	CO_2	74,100	kg/TJ
	CH_4	3.9	kg/TJ
	N_2O	3.9	kg/TJ
Production of Diesel [c)]	CO_2	7	ton/TJ
	CH_4	15.7	kg/TJ
	N_2O		
Diesel use in rubber mills	CO_2	74.1	ton/TJ
	CH_4	3	kg/TJ
	N_2O	0.6	kg/TJ
Production of LPG [c)]	CO_2	6	ton/TJ
	CH_4	16	kg/TJ
LPG use in rubber mills	CO_2	63.1	ton/TJ
	CH_4	1	kg/TJ
	N_2O	0.1	kg/TJ
Wood use in rubber mills	CO_2	110	ton/TJ
	CH_4	30	kg/TJ
	N_2O	4	kg/TJ

[1)] All emission factors are from IPCC (2006), except a) from Pluimers (2001); b) from EGAT (2008); c) from Lewis (1997).

4. RESULTS

4.1 Emissions from Rubber Plantations (Fresh Latex Production)

Emissions from rubber plantations include carbon and nitrous oxide emissions (I) due to land conversion, (II) from the production of raw materials used in rubber plantations, and (III) from the rubber plantations (Table 3). Emissions from land conversion presented in Table 3 are for the case that tropical forest is converted to rubber plantations. Replacing tropical forest by plantation results in a net loss of carbon to the atmosphere, since the above-ground biomass carbon, below-ground biomass carbon, and soil carbon in tropical forests is higher than in rubber plantations. Carbon in above-ground biomass, below-ground biomass, and soils in tropical forests are 235, 87, and 57 ton C/ ha, respectively (IPCC, 2006; Reijnders and Huijbregt, 2006), whereas for rubber plantations these values are 103, 57, and 40 ton C/ha, respectively (Gnanavelrajah et al., 2008). Following equation 2, we calculate the overall loss of carbon from the above-ground, below-ground, and soil carbon to be 132, 30, and 26 ton C/ha, respectively, and the annualized emissions 6.6, 1.5, and 1.3 ton C/ha/ year, respectively. The emissions are then converted to ton CO_2-equivalents/ton of fresh latex, assuming a yield of 5.64 ton fresh latex / ha/year (Table 3).

Annual greenhouse gas emissions from rubber plantations are about 6.4 ton CO_2-eq/ ton fresh latex/ year, but only 0.2 ton CO_2-eq/ton fresh latex/ year when emissions from land conversion are excluded. In case the rubber is planted on forested land, carbon loss from ecosystems account for 97% (over 6 ton CO_2-eq / ton fresh latex) of the total greenhouse gas emission from rubber plantations. The large contribution of C loss due to land conversion that we estimate for those rubber plantations is in line with earlier studies for palm oil plantations (Reijnders and Huijbregt, 2006), indicating that C losses from converting forests to palm oil plantations account for 60-80% of the total greenhouse gas emissions, and 90% in case oil palm is planted on peaty soils. We assume that all forest clearance for rubber plantations is done by logging, but in fact forests are also cleared by burning. Forest burning also releases CH_4, N_2O and CO, which we ignore here. As a result, we may be underestimating total greenhouse gas emissions to some extent (see for instance, Danielsen et al.(2009)).

As indicated above, most Thai rubber plantations were first planted about 60-80 years ago. For these plantations we consider no change in soil carbon stock, assuming that it takes about 20 years to reach a new equilibrium. The resulting greenhouse gas emissions are then 0.2 ton CO_2-eq/ton fresh latex, of which 60% (117 kg CO_2-eq / ton fresh latex) from the production of raw materials, and 40% (82 kg CO_2-eq / ton fresh latex) from the plantations. These emissions are largely associated with the production and use of synthetic nitrogen fertilizers. Although emissions from the production of N-fertilizer (process related) and the use of N-fertilizer may seem low (0.3 and 0.2 kg N_2O/ ton fresh latex), they are dominant in terms of CO_2-equivalents. We may have overestimated these emissions to some extent, since the actual amount of fertilizers used by farmers may be lower than as recommended by the Thailand Rubber Research Institute, from which we acquired the information. Production of diesel and its uses for tillage and transportation of latex are found to be minor contributors to greenhouse gas emissions.

Table 3 Greenhouse gas emissions from fresh latex production in rubber plantations

Activities	Emission (kg/ton fresh latex)			
	CO_2	CH_4	N_2O	CO_2-eq
I. Land conversion from forests to rubber plantations [1)]				
C above-ground loss	4,288	0	0	4,288
C below-ground loss	975	0	0	975
Soil carbon loss	834	0	0	834
N_2O direct emission from cultivation of mineral forest soil	0	0	0.24	74
Total	6,097	0	0.24	6,171
II. Production of raw materials used in rubber plantations				
Production of N- Fertilizer: energy related	30	< 0.001	0.001	30
Production of N- Fertilizer: process related	0	0	0.26	82
Production of P-fertilizer: energy related	4	< 0.001	< 0.001	4
Production of diesel use for tillage	0.17	< 0.001	0	0.17
Production of diesel use for latex transportation	0.67	< 0.001	0	0.67
Total	35	< 0.001	0.26	118
III. Emissions from plantations				
N_2Odirect emission from N -Fertilizer use	0	0	0.19	59
N_2O indirect emission after N leaching and runoff	0	0	0.04	13
N_2O indirect emission after emission of fertilizer N as NO_x and NH_3	0	0	0.02	6
Diesel use in tractor for tillage	0.4	< 0.001	< 0.001	0.4
Diesel use in latex transportation by pick-up car	7	< 0.001	< 0.001	7
Total	7.4	< 0.001	0.25	85

[1)] These estimates refer to the case that tropical forest has been converted to rubber plantations; for relatively old rubber plantations (> 60 years) on cultivated land, typical for the south of Thailand we assume these emissions to be zero.

4.2 Emission from Rubber Mills

Greenhouse gas emissions from rubber mills are presented in Table 4. We distinguish between emissions from the production of raw materials used in rubber mills, and emission from the industrial production of the three primary rubber products: concentrated latex, STR 20 and RSS. Electricity and fuel use are important sources of greenhouse gas emissions for all three rubber products. The emissions associated with the production of STR 20 (307 kg CO_2-eq/ ton STR 20) are higher than of concentrated latex, and RSS. This is because the STR 20 production is mainly a mechanical process and relatively energy intensive. Electricity is used for driving machines, including crepers, shredders, slab cutters, pre-breakers, rotary cutters, and packaging machines (Korwuttikulrungsee, 2002). Diesel and LPG are used in the drying process. In the past only diesel was used. LPG, giving rise to lower greenhouse gas emissions, has been introduced in block rubber production a few years ago, in response to rising diesel prices. For concentrated latex emissions from electricity production have the largest share. Electricity is mainly used in the centrifugation process, which separates latex from water and other substances in order increase the dry rubber content (Nguyen, 1999). However, the production of ammonia is another major source, accounting for 40% (57 kg CO_2 - eq/ton concentrated latex) of total greenhouse gas emissions. Ammonia is used to prevent latex coagulation. We estimate greenhouse gas emissions from RSS to be relatively low: 20 kg CO_2-eq/ ton RSS. This is excluding CO_2 from biomass combustion (~ 100 kg CO_2-eq/ ton RSS), because the wood used as fuel for drying and smoking the rubber sheet is from trees that are likely replanted.

4.3 Overall Emissions

So far, we presented greenhouse gas emissions during the production of fresh latex in rubber plantations (section 4.1) and the consecutive processing to primary rubber products in rubber mills (section 4.2) separately. Here we combine these estimates in order to present the overall emissions associated with the production of concentrated latex, STR 20, and RSS.

The results are presented for two cases; 1) relatively young (< 20 years) rubber plantations on converted forest land, and 2) relatively old (> 60 years) rubber plantations on cultivated land (Table 5).

Case 1 is typical for rubber products derived from latex produced in eastern and north-eastern Thailand (30% of the rubber plantations). For case 1 the greenhouse gas emissions from the production of concentrated latex, STR 20, and RSS are 13, 13, and 21 ton CO_2-eq/ ton product, respectively. This case assumes that rubber trees were planted on forest land. Emission associated with carbon stock loss from ecosystem account for more than 92% of the total emission. For case 2 the emissions are much lower, since it considers carbon loss due to land conversion negligible. The resulting emissions from the production of concentrated latex, STR 20, and RSS are 0.54, 0.7, and 0.66 ton CO_2-eq/ ton product/year, respectively for case 2. This large difference between case 1 and case 2 illustrates the large impact on the environment of converting tropical forests to rubber plantations.

Case 2 is typical for most (70%) of the rubber plantations in Thailand, located in the southern part of the country. We therefore further analyze the results of this case in more detail. It is clear that emissions from rubber plantations exceed emissions from rubber mills, for concentrated latex and RSS (Fig. 3). The relative shares of rubber plantations in overall greenhouse gas emissions are 70% and 95%, while rubber mills account for 30% and 5% of the overall emissions of conc. latex and RSS, respectively. In case of STR 20 energy related emissions have a large share in emissions (44%) from rubber mills. The production and use of synthetic N fertilizers is the most important source of greenhouse gases for all three products. The industrial production of fertilizers accounts for about 30-50% of total emissions. The biogenic emissions from fertilized soils account for another 20-30% to total emission. Emissions from electricity and fuel uses contribute by about 20%, 44%, and 3% to the emissions for concentrated latex, STR 20, and RSS, respectively. Even though emissions from rubber mills are lowest for RSS production (Table 4), the overall emissions are relatively high for RSS (Fig. 3). This is because for each ton of RSS, 3.3 tons fresh latex is needed. For the other two products the ration of fresh latex to primary product is lower.

Table 4 Greenhouse gas emissions from rubber mills (in kg CO_2-eq/ ton product)

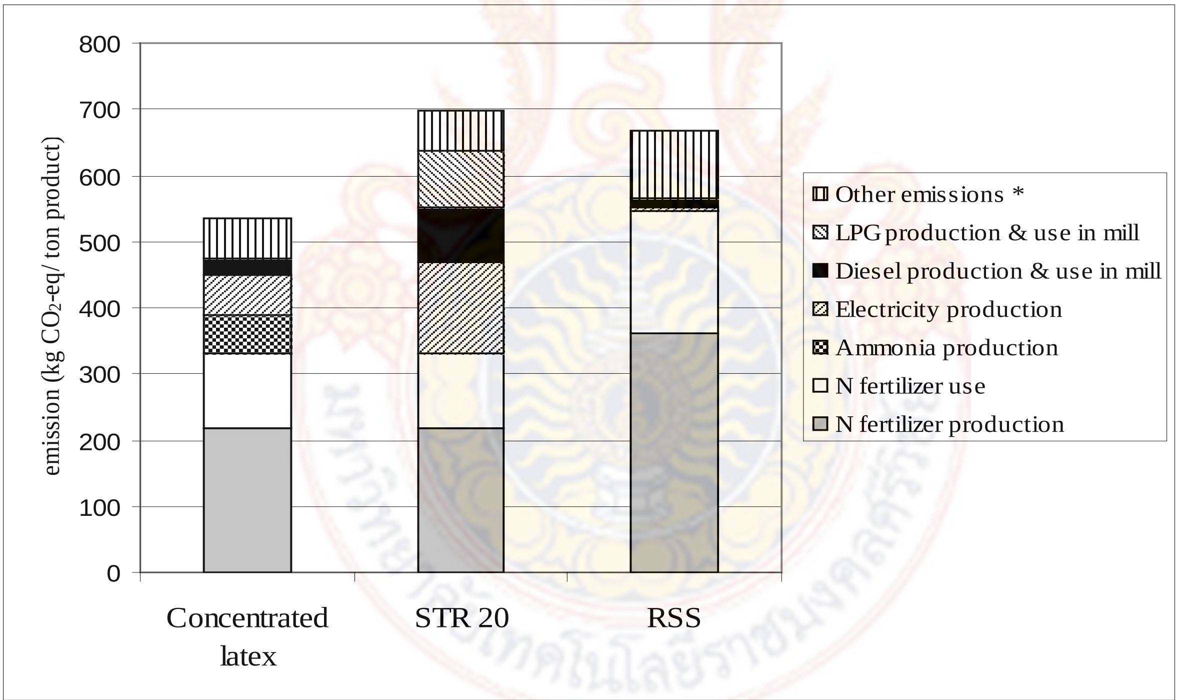
	Concentrated Latex				Block Rubber (STR 20)				Ribbed Smoked Sheet (RSS)			
	CO_2	CH_4	N_2O	CO_2-eq	CO_2	CH_4	N_2O	CO_2-eq	CO_2	CH_4	N_2O	CO_2-eq
I. Production of raw materials used in rubber mills												
Production of electricity :	62	0.1	0.2	63	137	0.1	0.3	138	6	0.01	0.02	6
Production of diesel :	2	0.1	0	2	7	0.4	0	7	1	0.1	0	1
Production of LPG	0	0	0	0	8	0.5	0	8	0	0	0	0
Production of ammonia	57	0	0	57	0	0	0	0	0	0	0	0
II. Emissions from rubber mills												
Diesel use	22	0.02	0.1	22	74	0.08	0.2	74	11	0.01	0.03	11
LPG use	0	0	0	0	79	0.03	0.04	79	0	0	0	0
Fuel wood use	0	0	0	0	0	0	0	0	99[1)]	0.7	1	2
Total	143	0.2	0.2	144	305	1	1	306	18	1	1	20

[1)] Emissions of CO_2 from fuel wood use are not included in total emissions, since this fuel wood is derived from the rubber trees that are replanted.

Table 5 Comparison of overall greenhouse gas emissions (in ton CO_2-eq/ ton product) associated with the production of primary rubber products for the two cases.

Product	Case 1: produced from latex from relatively young plantations on deforested land	Case 2: produced from latex from relatively old plantations on cultivated land
Concentrated latex	13	0.54
Block rubber (STR 20)	13	0.70
Ribbed smoked sheet (RSS)	21	0.66

Figure 3 may help in prioritizing options to reduce greenhouse gas emissions from rubber production in southern Thailand. First priorities may be options to reduce emissions from the use and production of synthetic fertilizers. To a lesser extent, emissions from the use of electricity and fuels may be of interest. In the next section, we will discuss cleaner technology options for these sources of greenhouse gases in some more detail.



* Other emissions include emissions from P fertilizer production, diesel production and use for tillage and latex transportation, and indirect N_2O emission.

Figure 3 Greenhouse gas emissions from the production of concentrated latex, STR 20 and RSS for Case 1 (assuming that rubber trees are not planted on recently deforested land). Emissions from plantations and rubber mills are included.

It should be noted, that all our estimates are surrounded with uncertainties. There are a few sources of uncertainties. First of all, we aimed at using local information, but that was often not available. In those cases we used internationally accepted methods such as the IPCC Guidelines for National Greenhouse Gas Inventories. These include default emission factor approaches that are considered generally applicable to world countries. Despite the wide acceptance of these Guidelines as best practice approach for estimating national emissions, it is in many cases better to use local information. But even if local information was available, there are uncertainties involved. Almost all emission estimates required up or downscaling to the national level of Thailand. And finally, we had to make many assumptions on the two cases presented here. Despite all these uncertainties, we are convinced that our study present the best estimate possible at present, using the most appropriate mix of local and international databases.

5. REDUCING GREENHOUSE GAS EMISSIONS FROM RUBBER INDUSTRIES

5.1 Site selection on rubber plantation

In the previous section, we quantified emissions of greenhouse gases per ton of primary rubber product, and showed that the overall emissions first of all depend on the history of the rubber plantations. Annual emissions are 13-21 ton CO_2-equivalents per ton of rubber in case a forest was cut recently to start the rubber plantation. In case the plantations are located on cultivated land, the emissions per ton of rubber product are 0.7 ton CO_2 equivalents/ton product or less.

A very effective way to avoid future greenhouse gas emissions from the rubber industry is to prevent that more forests are converted into rubber plantations. This is in line with other recommendations to avoid deforestation for other types of plantations in Southeast Asia, such as for palm oil (Reijnders and Huijbregt, 2006; Philips et al., 2006). Forest conversion to rubber or palm oil plantations not only results in carbon stock loss, but also poses a threat to biodiversity (Murdiyarso et al., 2002; Aratrakorn et al., 2006). These, and other considerations, need to be taken into account when expanding rubber plantation sites in forested areas in eastern and northeastern areas of Thailand. A better alternative may be to plant rubber trees on land where crops have been cultivated with a lower biomass carbon stock than rubber (200 ton C/ha), such as cassava (30 ton C/ha), eucalyptus (80 ton C/ha), or sugarcane (38 ton C/ ha) [29]. This could in fact result in a carbon may become less favourable for rubber plantations. Already today rubber plantations seem to be moving northwards because of increased rainfall which may, or may not be caused by climate change. These trends pose a realistic threat to tropical forests. It should be noted, that also the rubber plantations on cultivated lands in the south are probably located on lands that were at some point forested. However, we decided to not assign these historical emissions to the rubber products, because in the case of Thailand, this deforestation took place more than 60 years ago, and often not because of rubber production, but for other reasons. This is in line with the IPCC Guidelines on Greenhouse Gas Emission Inventories (IPCC, 2006). However, we realize that this is a matter of discussion, and that one could argue that also historical emissions need to be accounted for. We, however, chose not to do so, because including historical emissions would make the calculations not only overly complex, but also make the results less suitable for a discussion on minimizing emissions in the future.

5.2 Energy use efficiency in rubber mills

There are several ways to improve the energy efficiency of rubber production. In the production of concentrated latex, 90% of the electricity is used in the centrifugation process (STO, 2005). A study by the Thai Department of Industrial Work suggests that installation of inverters to centrifugal machines could improve the energy efficiency (DIW, 2001). Moreover, if old centrifugal machines (clutch and gear systems) are replaced by new machines (variable pulleys), a 20% reduction of electricity use could be achieved (DIW, 2001). In case of STR 20, DIW (2001) suggests that use of high efficiency motors and regular maintenance of cutters and shredder machines could reduce electricity use by about one-third. It should be noted that the emission factor for electricity production will change over time and may be lower when more renewable sources of energy are implemented in Thailand.

Diesel and LPG are used for drying during the production of STR 20. Most STR 20 mills in Thailand can improve their energy efficiencies. Complete combustion is not current practice, and drying times can be optimized. A typical problem is that the capacity of drying chambers is smaller than that of the cleaning process. As a result, drying chambers are used more than needed. Energy efficiency improvement through, for instance, improved controlling of rubber moisture and combustion conditions, may reduce fuel use by about 15% (DIW, 2001). Kongchana et al. (2007) suggested that drying rubber for 40 minutes at 130 ^{o}C, followed by 180 minutes drying at 110 ^{o}C has a better quality, and lower specific energy consumption as compared to current practice in many mills.

In RSS production the size and position of gas supply ducts and ventilating lids are often not optimal in smoking rooms (Promtong and Tekasakul, 2007). This significantly affects the circulation in the room. This non-uniform flow and the resulting large temperature variations in smoking rooms leads to inefficient use of energy (Tekasakul and Promtong, 2008). The energy requirement can be reduced by installation of insulators in drying chambers, moisture control of the rubber fuel wood, and the installation of fans to improve air circulation in smoking rooms (PCD, 2005). Installation of insulators may reduce the use of fuel wood by 770 kg/ year (PCD, 2005). Optimal design of smoking rooms, with appropriate temperatures (60 ^{o}C) and heat supply (11 kW) may reduce energy use by more than 30% (Tekasakul and Promtong, 2008).

In addition to energy savings and energy efficiency improvement, mills may switch to renewable sources of energy. Dutchaneekul et al. (2008) and Leong et al. (2003) for instance indicate that instead of diesel and LPG, renewable sources such as biogas from wastewater treatment may be used in mills producing STR 20. This would reduce greenhouse gas emissions. Also the electricity currently used is largely fossil based, and replacing this by electricity from solar panels, wind mills or hydropower would reduce emissions effectively. To what extent these are feasible options for rubber mills in Thailand needs to be investigated.

We may assume that it is technically possible to reduce greenhouse gas emissions from rubber mills by at least one-third, and probably more. Since mills account for 10-20% of the total greenhouse gas emissions from primary rubber products (case 2; Figure 3), these measures may reduce overall greenhouse gas emissions from primary rubber products (case 2) by an estimated 5-10%.

6. CONCLUSION

Our study is the first to quantify greenhouse gas emissions from rubber industry in Thailand. We first quantified emissions from rubber plantations, and showed that greenhouse gas emissions from the rubber industry largely depend on the history of the plantation. In case rubber trees were recently (< 20 years ago) planted on forest land, the emissions from land conversion are by far the most important source of greenhouse gases from rubber production. In that case, emissions from plantations amount to 6.4 ton CO_2-eq/ ton fresh latex/year. However, for older plantations on cultivated land, carbon losses from land conversion can be assumed to be zero, reducing emission associated with fresh latex production to 0.2 ton CO_2-eq/ ton fresh latex/year.

Second, we quantified emissions from rubber mills, that process fresh latex into primary rubber products. The emissions associated with the production of concentrated latex, STR 20, and RSS amount to 0.14, 0.3, and 0.02 ton CO_2-eq/ ton product, respectively.

We then calculated the overall greenhouse gas emissions from primary rubber products as the sum of emissions from rubber plantations and rubber mills. We compare three primary rubber products, and conclude that greenhouse gas emissions from block rubber (STR 20) are higher than from concentrated latex and ribbed smoked sheet (RSS), because of intensive energy consumption in the STR 20 mills. The overall emissions from RSS are high compared to emissions from mills, because more fresh latex is needed to produce RSS than to produce STR 20 or concentrated latex.

The overall emissions associated with the production of concentrated latex, STR 20, and RSS amount to 0.54, 0.70, and 0.64 ton CO_2-eq/ ton product, respectively. This is for the case that rubber plantations have been located on cultivated lands for more than 60 years. This is current practice in most of Thailand. Emissions are largely associated with energy use and the use of synthetic fertilizers. We also quantified emissions for the case that tropical forests have been converted to rubber plantations relatively recently, which is a recent trend in Thailand. In this case the emissions are much higher because of carbon loss from land conversion: 13, 13, and 21 ton CO_2-eq/ ton product for concentrated latex, STR 20, and RSS, respectively. Although currently no greenhouse gas emission standard exists for rubber production, rubber entrepreneurs could use our results for benchmarking and/or improving their environmental performance.

We identify a number of options to reduce greenhouse gas emissions from rubber production, including a shift from synthetic fertilizer to animal manure, and a shift from fossil-based energy to renewable, as well as energy and fertilizer efficiency improvement. These options could reduce greenhouse gas emissions per ton of rubber produced by at least one-third. Our study may serve as an example for other rubber producing countries. The options identified here are not specific for Thailand, but could be applied by rubber farmers and rubber mills in general.

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